PHYSICS TELLS WHY

An Explanation of Some Common Physical Phenomena

ATOMIC ENERGY EDITION

By

OVERTON LUHR

Illustrated by

RUTH C. SCHMIDT

I wish to express here my deep gratitude to our friend Ralph Johnson, who prepared my husband's manuscript for publication.

FRANCES LUHR

INTRODUCTION

In 1927 the undersigned gave a laboratory course for advanced Physics students in which the students were assigned small research problems. To one member of this class, noted for an exceptionally high scholastic average, there was assigned a clever but by no means simple problem on the recombination of gaseous ions, suggested by Professor A. Joffe of Leningrad, then a visiting professor at the University of California. Though the experimental effects looked for turned out to be too small for detection, the ingenuity of the student, and his intelligent analysis of the difficulties, made it appear that in Overton Luhr there was promise of real research ability as well as proof of high scholastic attainments.

In the ensuing years this promise was amply fulfilled. In his last year of graduate work Luhr was awarded the much coveted Whiting Fellowship at the University of California. His Ph.D. thesis carried forward the rather startling work on ionic recombination initiated by Dr. Lauriston C. Marshall far beyond its early stages. On completion of his thesis Dr. Luhr was appointed to a one-year instructorship at the University of California to carry on further his new investigations on the analysis of gaseous ions, using a mass spectrograph. He then accepted one of the three-year rotating instructorships at the Massachusetts Institute of Technology, where he remained until 1934. In 1934 he was appointed Assistant Professor of Physics at Union College, Schenectady, New York, where he remained until his illness forced him to retire. His most brilliant research work was a direct measurement of the mass of gaseous ions, using the mass spectrograph, begun in 1930 at California and later carried to a brilliant conclusion at the Massachusetts Institute of Technology. Following this work he entered the field of study of nuclear physics, applying his knowledge of gaseous ions and mass spectroscopy to attempt to develop powerful ion sources for nuclear disintegration. His contributions in this field, begun in collaboration with Professor E. Lamar and later carried on alone at Union College, showed again his research ability, though at this time his failing health had begun to impair his ability to work. Never of a robust constitution, away

from the mild climate of California where he had grown up, and unsparing of his well-being in his zeal for research, he suffered several attacks of respiratory infections which interrupted his work for protracted periods. Time was too short to accomplish all he wished to do, so that on recovery instead of relaxing during the midsummer heat he drove on at his laboratory work. In doing so he developed a tubercular lesion which laid him up for a year. On his partial recovery he again began his researches before he had completely regained his strength, with the result that he became dangerously ill and retired to a hospital. During his long period of enforced absence from the laboratory he then turned to his next strong interest in life, the teaching of Physics. Second to research, he had loved the teaching of Physics. With his lucid, logical and orderly mind, he was a clear and inspiring teacher, beloved of his students both for his ability in exposition and his lovable, sympathetic and human qualities. With his rich cultural background and his many scientific interests, he had a unique ability for making the complex and obscure phenomena of Physics especially clear and simple to his students. It is thus not strange that in the long days of enforced rest he should have turned his efforts to expressing his thoughts about Physics in the language that the young student and the interested layman could easily follow. The book which resulted is, therefore, a tribute to his love for Physics and his interest in its popular and correct promulgation. To have accomplished successfully what so many have failed to accomplish in the writing of a sound, interesting, inspiring and scholarly popular book for the layman without the use of the terrifying mathematics which characterizes Physics was a proper culmination of a fine scientific career.

The book is interestingly and charmingly written. Its function of explaining in a simple fashion so many of the phenomena puzzling to the man in the street and the housewife in her kitchen is ably achieved. This book, written as it was from the sick bed, was Professor Luhr's last contribution to his beloved Physics. In the spring of 1942, with the book finished, believing himself pretty well recovered from his illness and happy in his renewed strength, he again turned to the physical laboratory—this time, however, to aid American Physics in serving the war effort. This return to work proved too much of an effort to a heart unduly strained by his long illness, and he succumbed suddenly on May 22, 1942. It is, therefore, most fitting that his last contribution to the field of work he loved so well

should be published as a treasured heritage, and it is also fitting that it should be published by The Ronald Press Company whose function it is to popularize science and bring it to the interested lay public.

LEONARD B. LOEB

San Francisco
February, 1943

PREFACE TO THE SECOND EDITION

Since this book was first published in 1943 there have been many exciting developments in physics. Radar, one of the most important secret weapons of the war, is now being used to make the air and the sea safer for peaceful travel. Man for the first time has sent a signal to the moon and has seen the returning echo. Military rockets, ranging in size from the bazooka missile to the colossal V-2, have played their role in the conflict and have opened up new vistas for the future of travel and transport beyond the earth's atmosphere. Jet-propelled aircraft and helicopters are common in the skies. Most striking of all, the energy of atomic nuclei has been released in large quantities, and the human race is faced with the dual problem of freeing itself from fear of atomic bombs and finding out how atomic energy can best be used for productive purposes.

These new developments do not make the book out of date. Rather, they make it even more pertinent and timely, for every one of these new things is an outgrowth of principles that have long been known. To make the recent marvels understandable needs only to describe them and to show how they are related to the more familiar things. This is the task of Chapters Thirteen and Fourteen, which are new in this Edition. The first twelve Chapters are little changed from the original edition.

The revision has been made by Ralph P. Johnson, who prepared Dr. Luhr's manuscript for its first publication. Ruth C. Schmidt contributes more of her lively drawings to illustrate the expanded text.

CONTENTS

CHAPTER ONE

OF THINGS IN GENERAL

I. *Why Study Natural Science?*

There are many reasons why a person might wish to learn something about natural science. Fundamentally, it seems probable that man has developed much of his scientific knowledge because his inborn curiosity has driven him to search for the ultimate truth. At the same time, this search for truth pays dividends in material advantages. Supposedly, science makes the world a better place in which to live, because science and invention are responsible for our modern conveniences and means of entertainment.

But let us be more specific and talk about individuals. An occasional person is so fascinated by science that he studies to make it his life work, becoming, usually, a teacher or a research worker. Many more people study pure science as a stepping stone to professions in which science is applied to practical problems—professions such as medicine, dentistry, scientific agriculture, and all branches of engineering. Still others become interested in some branch of science because of a hobby like photography or radio.

No doubt you can think of other reasons for studying science. As an educated person, you have a desire to keep up with what is going on in the world. You wish to be able to read intelligently about the latest miracles that have been performed in smashing atoms. Or when you tire of politics, wars, and the newest economic theories, you like to discuss with your friends the recent advances in endocrinology and the cure for cancer.

Conceivably, too, as an intelligent consumer, you find it profitable sometimes to have a little scientific knowledge. For example, as a result of your scientific reading you are prepared to take with a grain of salt the extravagant claims of Joe Blow and Co. who advertise that their amazing new reducing pills will enable you, harmlessly and painlessly, to take off ten pounds in a week. Or, when an overzealous electrical appliance salesman tells you that the more expensive of two 500-watt heaters is better because it gives more heat, you smile knowingly to yourself and say under your

breath, "buncombe." For the most elementary knowledge of electricity tells you that all 500-watt heaters not only consume the same amount of power, but must give out the same amount of heat.

Any one of these reasons for studying science is sufficient in itself. But if you are of a curious turn of mind, I should like to propose another—the reason in fact for the existence of this book. Do you ever stop to wonder about the scientific explanation of the things that you see happening around you every day? And have you ever tried to find out the answers to your questions? If not, you are missing a lot of fun, because many phenomena can be explained satisfactorily without using mathematics or even technical language. And once you know why a certain thing happens, you take an added interest in observing it, and also in observing and trying to explain other things that you had perhaps never even noticed before. Such an attitude of inquiry is what constitutes the scientific spirit.

Even trained scientists find it interesting and profitable to observe the everyday aspects of nature. In fact, they are probably better rewarded for their efforts than is the layman, because they know what to look for and how to interpret their findings. Not every scientist can have the good fortune, or perhaps the ingenuity, to invent another steam engine as did James Watt, reputedly by watching his mother's tea kettle. Recently, however, I heard a famous scientist tell how he had discovered a new and interesting property of matter by the simple process of playing with his bowl of soup. He found that when he turned the bowl and then stopped it suddenly, the liquid did not merely slow down and stop, but had a tendency to bounce back. Laboratory experiments showed later that this is an elastic property of certain liquids that had been overlooked. This same scientist has spent a considerable portion of several vacations in measuring the currents in the lake on which his summer cottage is located. The measurements probably resulted in no great contribution to science, but this man is so intensely interested in everything scientific that he could not rest until his curiosity about the lake currents was satisfied. There are still plenty of unknown or little understood phenomena all around us for anyone to investigate.

The trained scientist of this day and age does not make the mistake of simply observing nature and then sitting down to think about what he has seen. He knows that nature is almost always complex, and that only by making measurements under controlled and simpli-

fied conditions in the laboratory can he expect to interpret natural phenomena correctly. In this respect he has a tremendous advantage over Plato, Aristotle, and the other learned men of Ancient Greece who, despite their logical and able minds, so often reached erroneous conclusions about the most fundamental things.

Since the layman of the present day is limited in most cases to observation without a laboratory to fall back on, he should perhaps be warned by the example of the Greeks. In other words, he should not jump at conclusions. But with the sound background of present-day knowledge at his disposal, almost anyone will find life a little more interesting if he is able to explain some of the things that he sees around him. One is not limited necessarily to strictly natural occurrences. Rainbows, thunder and lightning, or the motion of the planets are all topics that may be discussed profitably. But there is also much of interest in electricity, mechanical gadgets, and optical instruments—things devised or controlled by man. It is the purpose of this book to discuss both natural and man-made physical phenomena.

II. *What Is the Scope of This Book?*

Before you venture further along the road to scientific knowledge, let me tell you a little more about the things that are to come. I have intimated already that we shall limit our discussions for the most part to phenomena that we encounter in everyday life. In other words, we shall stress the things that can be observed without the aid of laboratory equipment.

I shall hope to make the explanations understandable, and also to make them seem reasonable; but it will not be possible to prove every statement. If, sometimes, you doubt the truth of what appears in these pages, I can only refer you to the standard textbooks. Frequently you would find it necessary to go to advanced works of a highly mathematical nature in order to find a rigorous and complete proof. In many cases scientists have arrived at their present-day conclusions only after careful laboratory experiments, plus complicated inductive and deductive mathematical reasoning. And sometimes they still do not have the complete answers to their questions.

We shall further limit ourselves to topics that come under the general heading of *physics*. Fortunately, physics is a broad subject.

It includes such branches of science as mechanics, heat, sound, light, radiation, and atomic structure.

Do not be disturbed, however, if sometimes we stray over the fence into the fields of chemistry, astronomy, engineering, or biology. For even biologists often make use of physical methods; and most branches of engineering—electrical, mechanical, civil, etc.—were once included in the subject of physics, but broke away when they became important enough to justify their existence as separate sciences. As for chemistry and astronomy, it is often difficult to tell nowadays where these sciences end and physics begins.

The close relation between physics and chemistry may be illustrated perhaps by the following definitions that scientists are fond of quoting: "A chemist is a person who makes inaccurate measurements on very pure materials; a physicist is one who makes very accurate measurements on impure materials; while a physical chemist is one who makes inaccurate measurements on impure materials."

These rather uncomplimentary definitions are only partially justified; but it is a fact that in practice a chemist and a physicist may be working on identical problems. Both, for instance, might be engaged in smashing atoms, or in detecting impurities with a spectroscope, or in testing the strength of a new aluminum alloy, or in studying fluorescent light, or in measuring the explosive effect of a new bomb, or in solving any one of a hundred other research problems. There are still phases of each science that are not touched on by the other science. But the overlapping is considerable.

III. *What Is the Metric System of Units?*

We have noted already the importance of accurate and controlled measurements in the development of modern science. Obviously, if one is to make a measurement, he must have a standard or a unit to measure with. For example, the length of a room might be measured as 14 feet. The result is always stated in two parts: the name of the unit (here, the foot), and the number of these units contained in the measured quantity.

The choice of a unit for any measurement is dictated fundamentally by convenience. It is very convenient to have a set of units that is commonly agreed upon, and familiar to everyone. When we say that the room is 14 feet long, we do not have to describe what we mean by a foot, because this standard of length is in common use. It would be different if we had measured the room with

a broomstick, and had stated the length as 4 broomsticks. It is also convenient, obviously, to choose a unit neither too large nor too small for the quantity being measured. For distances much larger than the length of a room the mile might be a more appropriate unit than the foot; for distances much smaller, the inch might be more appropriate. Again, it makes for convenience if the various different-sized units used for measuring a certain quantity are simple multiples of one another. Our English system is faulty in this respect: the inch, foot, mil, yard, rod, fathom, furlong, mile, league and hand are all units of length, but the conversion factors among them are so various that it is a chore to remember them all.

It is a great convenience, too, to keep the number of different units that have to be learned and remembered as small as possible, by using combinations of a few basic units to build up new units as they are needed. For example, once the foot is agreed upon as a standard of length, it is not necessary to have an entirely new and arbitrary unit for measuring an area, since the square foot is obviously an appropriate unit of area. In the same way, volume can be measured in cubic feet, speed in feet per second, density in pounds per cubic foot, and so on. It turns out that three basic units, a unit of length, a unit of mass (inertia, or resistance to change of motion), and a unit of time, are all that have to be chosen arbitrarily. The units that are needed for measuring other quantities can then be built up out of these basic units.

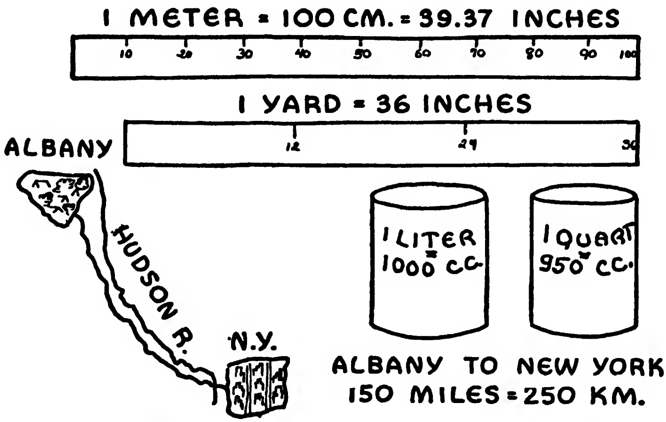
Measuring systems have usually grown up rather accidentally, each locality or each trade slowly evolving a set of units to serve its own needs, and these sets being gradually fitted together as best they might. The result, in the case of the English system, is a curious mess of units that are neither economical in number nor simply interrelated. We tolerate and use them, however, because they do have one of the properties any set of units should have—they are familiar and commonly used.

For convenience and world-wide uniformity, scientists have adopted and everywhere use the *metric system* of units. Since we shall have occasion in this book to use metric units, and because references to the metric system appear frequently in newspapers and elsewhere, let us see what the metric system is and how it originated.

In the metric system the unit of time, the *second,* is the same as in the English system. Therefore, of the three fundamental units,

only the metric standards of *mass* and *length* are at all unfamiliar to us.

The metric standard of length, the *meter*, is legally defined as the distance between two scratches on a platinum-iridium bar kept in the archives of the International Bureau of Weights and Measures near Paris. The standard of mass, the *kilogram*, is the mass of a platinum-iridium cylinder, also kept in the archives at Paris. Replicas of these primary standards are to be found at the Bureau of Standards in Washington, D. C., and in many other countries of the world. It is an interesting fact that the U. S. yard is legally defined by an act of Congress as 3600/3937 of a meter; while the pound is



Comparison of the English and Metric systems of units.

defined as 0.4536 kilogram. Hence, in the United States, our English units are now based on the metric system.

The metric system was devised by a committee of scientists in France at the time of the French revolution about 150 years ago. The meter was intended to be exactly one ten-millionth of the meridian distance from the equator to the pole of the earth. More recent measurements have shown, however, that the distance from the equator to the pole is actually 10,000,880 of the standard meters. The kilogram was supposed to be equivalent to the mass of 1000 cubic centimeters (one liter) of water at a temperature of 4° Centigrade (about 39° Fahrenheit). As in the case of the meter, the standard kilogram is slightly different from the value intended by the committee.

All other metric units are convenient decimal subdivisions or multiples of the standards. For example:

1 centimeter	=	1/100 meter
1 millimeter	=	1/10 centimeter
1 kilometer	=	1000 meters
1 gram	=	1/1000 kilogram

As an aid in visualizing the size of the metric units in comparison with the familiar English units, you might keep in mind the following approximate relations:

(1) A meter is a little longer than a yard.

(2) A centimeter is less than half an inch. There are about 30 centimeters in a foot.

(3) A kilometer is about 3/5 of a mile.

(4) A cubic centimeter is a volume about half that of an average-sized thimble.

(5) A liter (1000 cubic centimeters) is a little larger than a quart.

(6) A kilogram is a little more than two pounds.

(7) A gram is the mass of half a thimbleful (1 cc.) of water, and is a little more than 1/30 ounce.

CHAPTER TWO

SOME MECHANICAL PRINCIPLES AND THEIR APPLICATIONS

I. *What Are Newton's Laws of Motion?*

During ancient times and throughout the Middle Ages, Aristotle was the standard authority on most scientific matters. Today we can scarcely understand how anyone, let alone an authority, could be wrong so often. But Aristotle and the other Greek philosophers were observers and thinkers; they had no conception of the modern experimental point of view. Hence they often arrived at false scientific conclusions.

When Aristotle said that the natural state of all matter is a state of rest, he was correct as far as his observations went. Anyone can see that a stone thrown into the air, or a ball rolled along the ground, soon comes to a stop.

But what would happen if the stone were located out in space a million miles from the influence of the earth? Would it come to rest then, or would it keep moving? Aristotle did not know. He and his contemporaries could think of no way to find out.

Galileo (1564–1642), who is often called the father of modern experimental science, found the answer to this and to many other perplexing questions. In fact Galileo, almost single-handed, changed the whole outlook of the little world of science by the middle of the seventeenth century. He stressed experiment rather than philosophy. Galileo asked first, *What happens?* and only afterwards, *Why does it happen?* Before one can explain the motion of a stone projected into space, one must first determine just how the stone moves under various circumstances.

In the year of Galileo's death, one of the greatest scientists of all time, Sir Isaac Newton, was born. Like Galileo, Newton was an able experimenter. But he was more than an experimenter. He possessed a rare genius that enabled him to see far beyond the immediate results of his and Galileo's observations. He was able to generalize, to draw broad inferences, and to discover rules and laws

that were to serve as a basis for scientific developments in the centuries to come.

The Laws of Motion, based on the experiments of Galileo, were one of Newton's great contributions to science. Even to this day these three simple rules form the basis for the whole science of mechanics. True, when speed approaches the velocity of light, or when distance becomes astronomically great, Newton's Laws must be modified in accordance with Einstein's Theory of Relativity; but for practical mechanical problems here on earth, the laws of Newton give us the answers.

Newton's First Law of Motion: *Any object remains at rest, or continues to move at constant speed in a straight line, unless acted upon by some external force.*

The First Law of Motion obviously contradicts Aristotle's claim that the natural state of all bodies is a state of rest. Newton says that an object will keep on moving at constant speed in a straight line unless some kind of a push or a pull—a force like gravitation or friction—is applied to it. Thus a stone thrown into the air is pulled back to earth by gravity; and when the stone strikes the ground its rolling or sliding motion is stopped by frictional forces. If there were such a thing as a truly frictionless surface, the stone would slide on indefinitely at a constant speed.

We know that the planets revolve around the sun for many years with unchanging orbits. The planets, of course, are subject to the force of gravitation. Otherwise, according to Newton's First Law, they would fly off on a straight line into space. But their speeds of rotation remain constant, because there is practically no frictional force to slow them down.

Newton's First Law of Motion expresses the fact that matter possesses inertia—that objects resist changes in their states of motion. The inertia of a body is measured by its mass—grams, pounds, tons, etc. From common experience we know that the more massive a thing is, the greater the force required to start it moving—or to stop it once it is started. A greater force is required to start an automobile than a wheelbarrow; more braking force is needed to stop a freight train when the cars are loaded than when the cars are empty.

The rate of speeding up commonly is called acceleration; the rate of slowing down, deceleration. In science the one term acceleration is often used to designate both types of motion. The acceleration of your automobile is *positive* when force is supplied by the

motor through the wheels to speed the car up; the acceleration is *negative* when the retarding force of the brakes slows the car down. We even speak of acceleration when the car goes around a corner at constant speed—because a change in the direction of a motion requires a force just as does a change of speed.

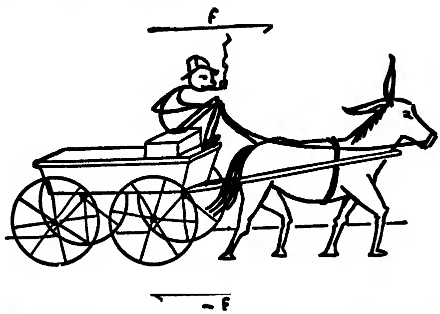
In any of these three cases, the greater the force supplied, the greater the acceleration. But when the car is more heavily loaded—that is when its mass is greater—the same force produces a smaller acceleration.

Newton's Second Law of Motion expresses the relation among force, mass, and acceleration, as follows: *The acceleration of a body is directly proportional to the force acting, and is inversely proportional to the mass of the body.*

The Second Law may be expressed more simply perhaps in the form of an equation:

$$\textit{Force} = \textit{Mass} \times \textit{Acceleration}$$

This is one of the most famous equations in all science. It is the starting point for every calculation involving changes in velocity, and with it one can solve numerous mechanical problems. Some of its applications will be discussed later.



Newton's Third Law of Motion. The horse pulls on the wagon with a force *F*, and the wagon pulls back on the horse with an equal and opposite force, – *F*.

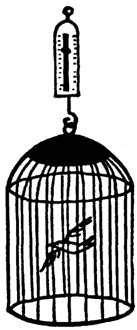
Newton's Third Law of Motion may be expressed as follows: *Forces always occur in pairs, and the two forces in a pair are equal and opposite.*

As an illustration of the Third Law, suppose that you are pushing on a door to open it; then the door pushes back on your hand with an equal and opposite force. Similarly, a book lying on the table pushes down on the table, and the table pushes back up on the book.

Note that the action and reaction, as Newton called the two forces of a pair, always act on different bodies—never on the same body. Also, action and reaction are equal even when an object is accelerated. Thus when you step on the throttle of your automobile, the earth pushes forward on the wheels of the car, while the wheels push back on the earth with an equal reaction. Both automobile and earth are accelerated (in opposite directions) according to Newton's Second Law; but the acceleration of the massive earth is far too small to be detected.

II. *Does a Flying Bird Weigh Anything?*

As a further illustration of Newton's Third Law of Motion, consider the following problem. Suppose that a bird weighing one pound is flying around in a five-pound cage. If you hung the cage



Does the spring balance indicate the weight of the cage alone, or of the bird plus the cage?

on a spring balance, would the scales record the weight of the cage alone, or the weight of the cage plus the bird?

There is a story connected with this problem. Some years ago, a graduate student in physics at a large university decided to have some fun at the expense of two of his professors. A newspaper reporter was made a party to the scheme, and was persuaded to call each of the two professors on the telephone in order to ask his expert opinion on a scientific question.

Professor A was asked the following question: If a one-pound bird is flying in a five-pound cage made of thin wire, how much will the combination weigh?

"Five pounds," Professor A told the reporter.

Professor B was then called, and a similar, but slightly different question was put to him: If a one-pound bird is flying in a five-pound cage made entirely of glass, how much will the combination weigh?

"Six pounds," replied Professor B without hesitation.

The next day, much to the embarrassment of the two prominent professors, headlines appeared in the local paper: UNIVERSITY PROFS DISAGREE ON SCIENTIFIC QUESTION. A carefully misworded account of the questions and answers followed, with the words *wire* and *glass* omitted.

No doubt everyone would agree that the bird and cage together would weigh six pounds, provided the bird were sitting stationary on its perch. But which of the professors was right in the case of the flying bird? The answer is that they were both right.

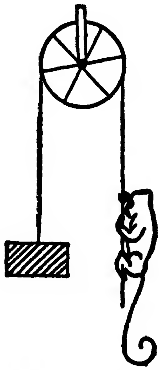
Since the bird is not falling, it must be supported by something. That something is the air. Because of the flapping of the bird's wings, the air pushes up on the bird with a force of one pound. The bird must then push down on the air with an equal and opposite force. This downward force of one pound is transmitted through the air to the first solid surface available. Since the wire cage would not have solid walls or floor, the air would push down, not on the cage, but on the ground below. Therefore, as Professor A said, the wire cage plus bird would weigh only five pounds. On the other hand, the glass cage would be impermeable to air, and in this case the weight of the bird must be borne by the cage. Professor B was absolutely correct when he said that the scales would then read six pounds.

There is a moral to this story about the bird in the cage. It illustrates the necessity for precise statement in a scientific problem. The question as we originally stated it had little meaning because it failed to specify the nature of the cage. The scales might read anything from five pounds, for a cage constructed of fine wire, up to six pounds for a cage made of some impermeable material like glass or tin. If the cage had holes in it, the weight would be something between five and six pounds; but the exact weight would be very difficult to calculate.

III. *Can You Solve the Problem of the Monkey on the String?*

When acceleration is involved, mechanical problems usually become more difficult. Even scientists, it is said, have sometimes been puzzled by the following problem involving a monkey climbing a string. Imagine a string passing over a pulley, with a monkey

hanging on one end of the string, and an iron bob on the other end balancing the monkey. Monkey and bob are equal in weight, and



What does the weight do when the monkey climbs up the string?

both are initially at rest. The weight of the string and the friction in the pulley can be neglected.

The question is this: What happens to the iron bob when the monkey begins to climb up the string? In other words, will the bob rise with the monkey, will it descend, or will it remain stationary?

To solve the problem we must apply Newton's Laws of Motion. When the monkey begins to climb, he is accelerated upward. Therefore, according to Newton's Second Law, the string must not only support the monkey's weight, but it must supply additional force for the acceleration. As a test of this conclusion, you might stand on bathroom scales sometime when you are going up in an elevator. You will find that as the elevator starts upward, the scales will register several pounds more than your weight. The added push upward on the bottom of your feet serves to accelerate your body. For a simpler experiment, one which can be done less conspicuously, hang a weight on a string, and jerk upward. You will feel a sudden added tension in the string as the mass is accelerated.

Even though the monkey moves upward by his own efforts, there must be an added tension in the string to provide force for the acceleration. By Newton's Third Law the tension in the string must pull equally on the iron bob. Therefore, the bob is accelerated upward just like the monkey. The solution to the problem, then, is this: the monkey and the bob rise together.

When the monkey stops climbing, and thus decelerates, the tension in the string is decreased, and the bob comes to rest at the same time as the monkey. Likewise, if the monkey turns and starts down the string, the bob descends with the monkey.

IV. *Why Is Direction Important in Mechanics?*

Before discussing additional applications of Newton's Laws of Motion, let us digress temporarily to talk about the importance of *direction* in mechanical problems. Some physical quantities have no hint of direction associated with them. Among these are mass, volume, and temperature. Such quantities are called *scalars.* On the other hand, many things like force, velocity, and acceleration are essentially directional in nature. These are called *vectors,* or *vector quantities.* The direction as well as the size or *magnitude* of these vector quantities must always be stated, or at least clearly implied, if the quantity is to have any real meaning. Thus, it is not sufficient for a captain to know that his ship is making 20 knots. He must know, as well, the direction of travel—north, south, east, west, or some point in between—if the ship is to make port safely instead of piling up on the rocks.

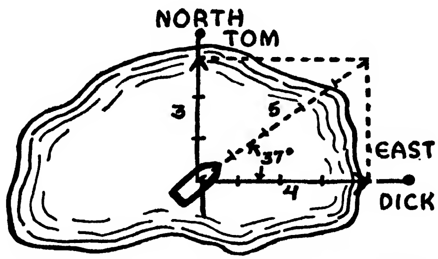
It is convenient to represent these vector quantities graphically, with the aid of arrows. The length of the arrow is a measure of the magnitude of the vector quantity, and the direction of the arrow gives the direction of the quantity.

I bring up these technical matters about vectors because we are going to have occasion to add two or more vectors together; and in the world of vectors, 2 plus 2 is no longer always equal to 4. In fact, 2 plus 2 may equal anything between zero and 4.

As an example, consider a toy boat in a pond with two strings attached to it. Suppose that a boy, Tom, pulls on one string with a force of 3 pounds, and another boy, Dick, pulls on the other string with a force of 4 pounds. If both boys pull in the same direction, the sum, or, as we say, the *resultant* of the two forces is simply 3 plus 4, or 7 pounds. However, if Tom pulls in one direction, and Dick in the opposite direction, the resultant force is 4 minus 3, or one pound in a direction toward Dick.

All this so far is easy and obvious. But suppose that Tom pulls toward the north on his string, while Dick pulls toward the east; that is, the two forces are at right angles to each other. *Now* what is the vector sum or resultant force? In other words, what is the direction and magnitude of a single force that would have the same

resultant effect on the boat as these two separate forces of 3 and 4 pounds? We are obliged to resort to geometry to find the answer. We draw an arrow pointing north, of length 3 units (centimeters, inches, or any other units we please), and another arrow pointing east, of length 4 units. These two arrows form two sides of a rectangle and they represent graphically the forces of 3 and 4 pounds. We now complete the rectangle, and draw a diagonal from the origin of the two forces to the opposite corner. The length of the diagonal (obtained by actual measurement or by the Pythagorean Theorem*) is 5 units, and it points about 37 degrees north of east. This arrow represents the vector sum or resultant of the two forces. The motion of the boat would be exactly the same, either with the two separate



Here, 5 pounds is the (vector) sum of 3 pounds plus 4 pounds.

forces of 3 and 4 pounds pulling on it at right angles, or with the single force of 5 pounds acting in the direction of the diagonal.

Tom and Dick might be pulling in other directions—for example, northeast and east. In any case, to find the resultant force graphically, we must complete the parallelogram, and measure the length of the diagonal.

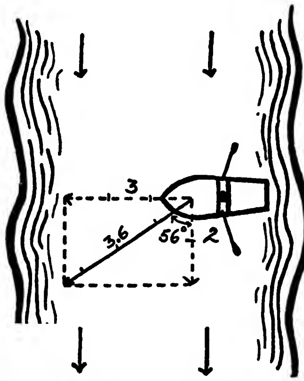
Velocities, having direction, are vector quantities, and they offer some problems of special interest. First, you should realize that all motion is relative. If you do not believe this, look out of the window of your train sometime when you are passing another train on the next track. If the trains are moving slowly, you cannot tell whether your train is moving and the other train is standing still; or whether both trains are moving. All you know is that you are moving *relative* to the other train. Ordinarily, without thinking about it, we measure our motion with the earth as the reference point. But

* In a right angle triangle, the square of the hypotenuse equals the sum of the squares of the other two sides. In this case, $(3)^2 + (4)^2 = (5)^2$.

when we lose sight of the ground, then we must use some other object as our reference, such as the train on the next track.

As another example of the same thing, imagine that you are the pilot of a fighter plane, in combat high above the earth—perhaps even above clouds, so that you cannot see the ground. Then you will not care at all how fast you are moving relative to the earth, nor in what direction of the compass. Your only concern, for the moment, will be to move relative to the enemy plane so as to place him in your line of fire and within range. Only after the engagement is over and you start for home will you need to know where you are and which way you are going, relative to the earth.

Considerations of this kind raise the question whether there is any such thing as absolute motion. The earth cannot be taken as the ultimate system of reference, since it rotates around the sun. Our solar system in turn moves relative to the stars in the heavens. Einstein, in his theory of relativity, says that the concept of absolute



A boat pointed straight across a river actually moves diagonally downstream.

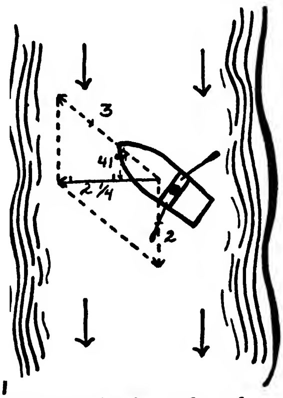
motion is nonsense, and that we should base all mechanics on the idea of relative motion.

Be that as it may, for our everyday problems the earth serves as a satisfactory reference point, and we can measure our motion relative to it.

But to return to the addition of velocities; have you ever noticed raindrops splashing on the window of a fast-moving train or automobile? Even though the rain is coming straight down relative to the earth, it strikes the moving windows on a slant. The direction of the splashes indicates the direction of the resultant of rain velocity

and vehicle velocity. The greater the speed of the vehicle, the more aslant the rain appears to a person riding inside. If the passenger puts his head out of the window, the rain seems to be driving almost horizontally into his face.

As another example, have you ever tried to row a boat or swim in a flowing river? Suppose that the river is flowing at the rate of 2 miles per hour, and that you are able to row 3 miles per hour in still water. Then, relative to the earth, you can row 3 plus 2, or 5 miles per hour downstream, but only 3 minus 2, or one mile per hour upstream. If you point the boat directly across the river, you travel straight across relative to the water; but while you are cross-



In order to travel directly from one bank to the other, the boat must be pointed obliquely upstream.

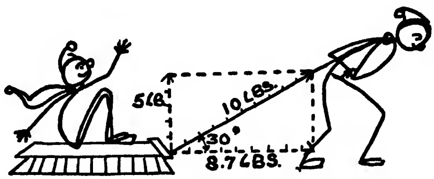
ing, the whole body of water moves downstream and you are carried along with it. Consequently, your resultant velocity relative to the earth is the diagonal of the rectangle with sides 3 and 2. You move at the rate of about 3.6 miles per hour at an angle of 56 degrees with the bank. If you actually wish to get straight across from one side to the other, you must point the boat upstream at an angle of 48 degrees with the bank. Then the resultant velocity is at right angles to the bank, but your progress across will be at the rate of only about $2\frac{1}{4}$ miles per hour. In the same way, ships and aeroplanes must set their courses to take into account cross currents of wind and water.

V. *Can a Sailboat Go Faster Than the Wind?*

So far we have had occasion only to add vectors. Often the reverse process, known as *resolution,* is necessary to solve a particular

problem. When we resolve a vector, we break it up into parts or *components*. In other words, we find its effect in one or more directions other than the direction of the vector itself.

Suppose, for example, that a boy pulls on a sled with a force of 10 pounds, by means of a rope slung over his shoulder. The sled moves along the level, but the pull of the rope is upward at some angle, say 30 degrees, with the horizontal. We can find the effective horizontal force pulling on the sled if we draw an arrow along the



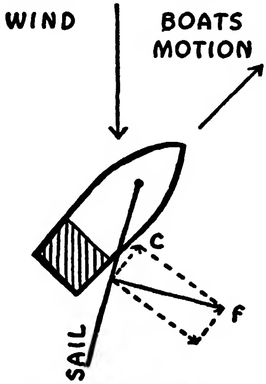
The component of the 10-pound force which is effective in pulling the sled is 8.7 pounds.

rope to represent the 10 pounds pull, and then drop a vertical line from the head of the arrow to the ground. The length of the line joining the base of this perpendicular with the tail of the arrow is a measure of the effective horizontal pull—in other words, the horizontal component of the 10-pound force. It turns out to be about 8.7 pounds. The vertical component, determined in a similar fashion, is 5 pounds. This upward force of 5 pounds helps to reduce the frictional resistance, but is otherwise wasted effort so far as pulling the sled is concerned. Reversing the process of resolution, it is apparent that the vector sum of the 5- and 8.7-pound components is the original 10-pound force.

The problem of tacking, or zigzagging against the wind, is one that confronts all people who sail a boat—at least, if they ever want to sail in the direction from which the wind is blowing. Would you be surprised to know that on a tack a boat can sometimes go faster than the wind itself? When a boat and the wind are going in the same direction, the speed of the boat is limited by the speed of the wind; but when the boat and the wind are traveling at right angles or even in almost opposite directions, there is no such limitation. Iceboat enthusiasts are well aware of this fact. Frequently they find it possible to speed along at 75 or 100 miles per hour in a 50-mile wind. In fact, it is said that the best iceboats are able to go 3 to 6 times as fast as the wind. Boats that sail in water encounter a much larger frictional resistance than do icebeoats. Consequently, a sail-

boat must be unusually well designed, if it is ever to exceed the velocity of the wind.

Let us see how our knowledge of vectors and their components enables us to explain the phenomenon of tacking. First of all, we must notice that the pressure of the wind against the sail is always at right angles to the sail's surface, irrespective of the direction of



Tacking. No matter what the direction of the wind, the force *F* is at right angles to the surface of the sail. *C* is the component of the force effective in driving the boat.

the wind. This somewhat surprising fact is a result of Pascal's Law of fluids, which we shall discuss later. Now then, the force against the sail may be resolved into two components: one along the direction of the boat's motion; the other at right angles, tending to push the boat sideways. Even though the component of force in the direction of motion is small, it is sufficient to keep the boat speeding along at a good rate, if the frictional resistance is likewise small. In fact, the ultimate speed of the boat is limited only by this friction, and not by the velocity of the wind.

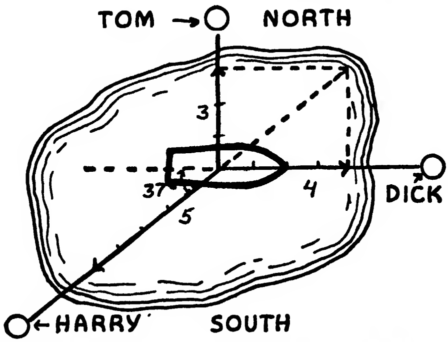
The component of force tending to push the boat sideways may be very large, but is rendered quite ineffective because the large area of the keel prevents much side-drift through the resisting water. In the case of an iceboat, the sharp runners cut into the ice and keep the boat on its course.

VI. *When Is a Body in Equilibrium?*

With what do you associate the word *equilibrium* in your mind? Do you think of an inebriated individual making his way somewhat unsteadily down the street? Or do you think of a tight-rope walker

balancing precariously in midair? Probably something of the sort. But do you realize that the term applies equally well to an automobile darting along a straight road at a constant speed of 60 miles per hour? From a scientific viewpoint, an object is in equilibrium, not only when it is standing stationary, but also when it is moving in a straight line at constant speed. On the other hand, if it is speeding up or slowing down (accelerating), or if it is going around a corner, then it is not in equilibrium.

This definition of equilibrium perhaps reminds you of Newton's First Law of Motion. You recall how it goes: a body remains at rest or moving in a straight line at constant speed, unless it is acted upon by externally applied forces. Evidently, then, whenever there are no forces at all pulling or pushing on a body, that body must always



The forces 3, 4, and 5 pounds just balance. Hence, the boat is in equilibrium.

be in equilibrium. But objects with forces acting on them may also be in equilibrium. But then, the forces must balance—their vector sum must equal zero. Thus, in the case of the speeding automobile, there are four forces acting; but they balance each other in pairs. The pull of gravity downward (the weight) is counteracted by the push of the road upward. The driving force supplied by the motor is exactly balanced by air resistance and other frictional forces. However, when the driving force is greater than the frictional resistance, the car is accelerated in accordance with Newton's Second Law.

When the forces on a body in equilibrium do not all pull along a single straight line, the situation becomes a little more complicated. Let us go back to our two boys, Tom and Dick, pulling with strings on a toy boat. You remember that when Tom pulled north with a

force of 3 pounds and Dick pulled east with a force of 4 pounds, the resultant was a force of 5 pounds in a direction 37 degrees north of east. Now suppose that we add a third boy, Harry. With what force and in what direction will Harry be required to pull, in order that the boat be in equilibrium? The answer is that he must just balance the resultant of the other two forces: he must pull with a force of 5 pounds in a direction 37 degrees south of west. The vector sum of the three forces is then zero.

But even though the vector sum of all the forces is zero, an object may still fail to be in equilibrium. It may have a tendency to rotate, unless the forces are all applied at a single point, or unless the tendency to rotate in one direction balances the tendency to rotate in the other direction. The effectiveness of a force in causing rotation is called *torque,* and it depends on two things: first, the force itself; and, second, the distance of the force from the axis of rotation. We commonly say that the *leverage* becomes greater as the force moves farther away from the axis. The torque is defined as the product of the force by the perpendicular distance of that force from the axis: $T = F \times P$.

As a simple example of the importance of this second condition for equilibrium (namely, that the tendency to rotate, or the total torque, must be zero), let us turn once again to a child's amusement device, the ordinary see-saw. If Tom, weighing 100 pounds, sits on one end of the board, and Dick, weighing 120 pounds, sits on the other end, the two boys certainly will not balance each other, even though the vector sum of all the forces on the board is zero—that is, even though the weight of the boys plus the board is balanced by the push upward at the pivot. There would still be a tendency to rotate, with Tom's end of the board going up in the air. But now, suppose that Tom (100 pounds) is seated at the end of the board, 6 feet from the pivot; where must Dick (120 pounds) sit in order that he may just balance Tom's weight? The torques must be equal:

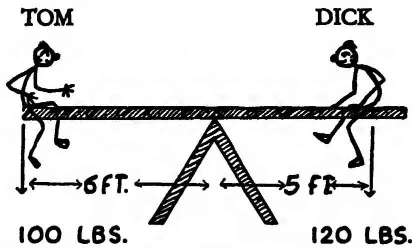
$$100 \text{ (lbs.)} \times 6 \text{ (ft.)} = 120 \text{ (lbs.)} \times X \text{ (ft.)}$$
$$X = 600/120 = 5 \text{ ft.}$$

Dick must sit 5 feet from the center to balance Tom.

To sum up, then, there are always two requirements for equilibrium: first, the vector sum of all the forces acting on a body must be zero; and, second, there must be no tendency to revolve; that is,

the torque trying to rotate the body in one direction must balance the torque in the opposite direction.

We shall again meet this second condition of equilibrium, when we talk about levers and other machines in the next chapter. In the meantime, let me point out the importance of this whole matter of equilibrium in the design of engineering structures. If a bridge or a

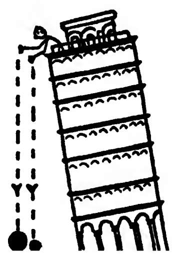


Tom and Dick balance each other on the see-saw.

skyscraper is to stand without falling, each of its parts must evidently be in equilibrium. The science of *Statics* (equilibrium of rigid bodies), together with a knowledge of the strength of materials, constitutes the basis of all civil engineering computation and construction.

VII. *How Do Objects Rise and Fall?*

Historically speaking, the problem of falling bodies is one of the most famous in all science. The Greeks were unable to agree about the matter. Aristotle, as usual, was wrong, but not as wrong as he

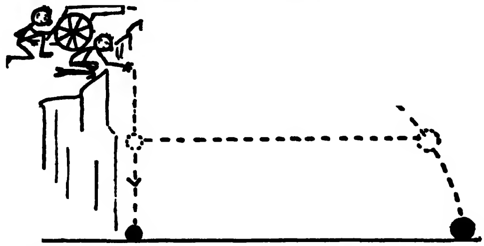

Galileo reputedly dropped different-sized balls off the Leaning Tower of Pisa to demonstrate that light and heavy objects fall at the same rate.

might have been. He said that heavy bodies fall faster than light ones; but that all bodies would fall at the same rate in a vacuum. But he scoffed at the possibility of ever attaining a vacuum.

Galileo, about the beginning of the seventeenth century, was probably the first man in history to gain any real insight into the nature of the uniformly accelerated motion of falling bodies. According to legend, Galileo went so far as to demonstrate his conclusions publicly by dropping a large ball and a small ball simultaneously off the Leaning Tower of Pisa. The balls struck the ground together. Even then, apparently, the good people of Pisa did not believe their own eyes—any more than you believe that you have actually seen a magician cut a woman in half with a buzz saw. As a matter of fact, Galileo was fudging just a little. Because of air resistance, the smaller of the two balls should have lagged a tiny bit behind the heavier one. The smaller an object, the relatively greater becomes the air resistance. Likewise, the lighter an object, the greater the retardation due to air resistance. Thus, if you dropped a wooden ball and a steel ball together, each of about 2 inches diameter, you might expect that the steel ball would be 2 or 3 feet ahead of the wooden ball after they had fallen 100 feet. Eventually, after falling a long distance (say, a mile), the balls would attain a constant velocity, with the force of gravity just balanced by the opposing air resistance. This terminal velocity would be greater for the iron ball than the wooden one. A very light object, such as a feather, floats downward with a small terminal velocity, which it usually attains after dropping only a few inches.

However, over very small distances, or in a vacuum, all objects fall exactly together, and continue to gain speed indefinitely. A feather and a lead shot drop side by side in an evacuated tube. Newton's Second Law of Motion requires that they do exactly that. *Acceleration* equals *force* divided by *mass*. The greater the mass of a body, the greater the pull of gravity—but, also, the greater the inertia to be overcome. Therefore, the acceleration downward is the same for all bodies whenever air resistance can be neglected. This *acceleration of gravity*, designated usually by the symbol g, is equal to approximately 32 feet per second per second (980 centimeters per second per second). It varies slightly from place to place on the earth, but at any one spot is the same for all bodies no matter what their weight. A freely falling object is traveling at the rate of 32 feet per second at the end of the first second; 32 plus 32, or 64 feet per second at the end of the second second; 64 plus 32, or 96 feet per second at the end of the third second; etc. Incidentally, 32 feet per second is equivalent to about 22 miles per hour.

The motion of a body thrown straight upward or dropped straight downward is simple enough. But the motion is more complicated when a projectile starts out in a direction other than vertical.



The two balls, starting at the same time and from the same height, strike the ground together.

Let us consider the case of a gun fired horizontally from the top of a cliff. Perhaps it does not occur to us ordinarily that a bullet fired in this way starts to fall the instant it leaves the gun, just as though it had been dropped. Such is the case, however. If a rock is dropped over the edge of the cliff at the same time the bullet is fired, rock and bullet (except for small air-resistance effects) will strike the level ground beneath simultaneously. In other words, the horizontal motion of the bullet in no way interferes with its falling motion due to gravity.

The resultant velocity at any instant is always the vector sum of the constant horizontal velocity and the increasing vertical velocity. Consequently, the bullet follows a curved (parabolic) path, sloping always downward at a steeper angle as the speed of fall becomes greater. A stream of water ejected horizontally from a hose nozzle follows the same sort of path.

If you have seen newsreel pictures of bombs dropped from aeroplanes, you have probably noticed that the bomb at first follows along directly under the plane, and then gradually noses over and falls more nearly straight down. If the forward motion of the bomb were not slowed down by air friction, and if the bomber continued in level flight at constant speed after releasing the bomb, the bomb would continue to be directly under the plane until it struck the ground.

An especially interesting case arises when a projectile is hurled from the rear of a fast-moving train or other vehicle. Let us suppose that someone throws a stone, horizontally, down the track from the rear platform of a train speeding along at 60 miles per hour. And

suppose that the stone is thrown at an initial speed of 60 miles per hour (relative to the train, of course). Then, to the people on the train, the stone will appear to follow a perfectly normal parabolic path. But how will it seem to a person standing on the ground alongside the track? Remember that velocity is always relative. The forward motion of the train will just cancel the backward motion of the stone. In other words, the stone will plummet straight down to the ground, with no motion at all in the horizontal direction.

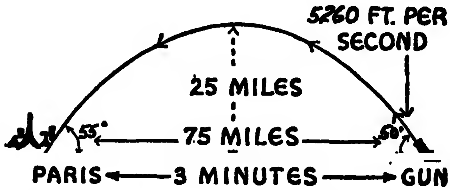
A similar situation arises when a bullet is fired from a speeding aeroplane. A revolver bullet, for instance, has a muzzle velocity of only about 500 miles per hour. If such a bullet is fired from the rear of a modern warplane speeding along at 500 miles per hour, the two velocities cancel, and the bullet at first stands still momentarily —then falls straight down as though it had been dropped. On the other hand, if the bullet is fired from the front of the plane, the velocities add, and the speed of the bullet relative to the earth is 1,000 miles per hour. Of course, the machine guns used in warfare fire their bullets at speeds much greater than 500 miles per hour. Moreover, if the target is another moving plane, it is the speed of the bullet relative to this moving target that counts in determining the damage done—not the speed relative to the earth. It makes no difference at all whether a revolver bullet stands still with respect to the earth and you run into it with a speed of 500 miles per hour, or whether you are standing still with respect to the earth and the revolver bullet strikes you with this speed. In both cases the effect is the same, and unpleasant for you.

When a projectile is fired upward at some angle, it follows a bowed path which is strictly parabolic if air resistance may be neglected. Such things as maximum height, time of flight, and range can be calculated mathematically if the initial velocity and angle of projection are known. It turns out that the maximum range (maximum distance of flight measured along the level) is attained when the angle of projection is 45 degrees upward. For example, neglecting air resistance, the maximum range of a 22-caliber rifle bullet (initial speed about 700 miles per hour) would be nearly 6 miles. Actually, air resistance reduces its range to something like one mile. Nevertheless, it is very dangerous to fire a gun haphazardly into the air. The bullet travels surprisingly far.

Incidentally, if you are standing on the edge of a cliff and wish to throw a stone so that it will land as far as possible from the base

of the cliff, you should project the stone, not horizontally, but upward at an angle of 45 degrees. Few people seem to know this.

The effect of air resistance is none too easy to calculate, and this phase of the problem offers one of the major difficulties in determining the range of large modern cannon. During the first World War, the German "Big Berthas" threw 8-inch diameter shells into



During the World War, the German "Big Berthas" threw shells into Paris from a point 75 miles away.

Paris from a distance of 75 miles away. These shells were projected upward at an angle of 50 degrees with the horizontal, so that they traveled a good part of the distance in the stratosphere where air resistance is negligible. The initial velocity was nearly one mile per second, and the shells rose to a height of more than 25 miles above the ground. The time of flight was about three minutes. Air resistance slowed the projectiles down as they returned to the denser atmosphere, and they fell at such a large angle that the residents of Paris thought the shells were raining straight down out of the heavens above—in fact, it was rumored at first that they were bombs dropped from German planes at high altitude.

VIII. *What Is Momentum, and What Does It Do?*

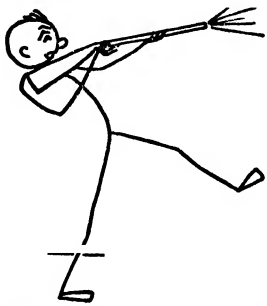
If you have ever pulled the trigger of a loaded shotgun or high-powered rifle, you know that the gun kicks back sharply when it is fired. When you jump out of a rowboat onto a pier, the boat recoils in the opposite direction, and you may receive a ducking if you are not careful. In a sense these are illustrations of Newton's Third Law of Motion: action and reaction are equal. Better yet, they are examples of the *Conservation of Momentum*—an important mechanical principle based on Newton's Laws of Motion.

Momentum is sometimes called the quantity of motion. More precisely it is defined as the product of mass times velocity:

Momentum $= MV$

A loaded freight car has greater mass and therefore more momentum than an empty car, provided both are moving at the same speed. But a fast-moving empty car may have more momentum than a slow-moving loaded car. The mass of the empty car is relatively small, but at high speed its MV is great.

Now, it requires force in order to change momentum. This fact should be evident if we recall that Newton's Second Law demands a force for the acceleration of any object. If an automobile is accelerated, its momentum increases as its velocity increases. As a matter of fact, Newton himself stated the Second Law in terms of



A gun kicks back when it is fired. The momentum of the gun is equal and opposite to the momentum of the bullet.

momentum change rather than acceleration. He said that the rate of change of momentum is proportional to the force acting.

It is further evident that the momentum of a single body or of an isolated group of bodies must remain constant when the externally-applied forces are small enough to be neglected. If a gun and its bullet, for example, are initially at rest, their momentum is zero. Firing the gun does not change that situation. The total momentum is still zero. The forces are internal rather than external, and the momentum of the bullet in one direction just balances the momentum of the gun in the opposite direction. We might write a simple equation to express this fact:

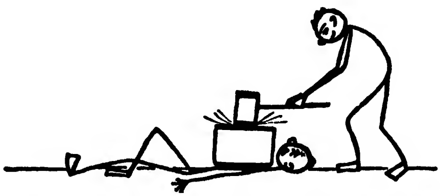
$$\underset{\text{(bullet)}}{mV} = \underset{\text{(gun)}}{Mv}$$

The bullet has small mass and large velocity; the gun of large mass kicks back with relatively small velocity.

The Principle of the Conservation of Momentum may then be expressed as follows: *When the external forces acting on a mechanical system can be neglected, the total momentum of the system remains constant.*

There are many examples of the conservation of momentum other than those already mentioned. When two billiard balls collide the momentum before impact always equals the momentum after impact. Thus the cue ball stops dead when it strikes another ball head on. The ball struck takes up the momentum. In the case of a "follow" shot the cue ball rolls on forward; or in a "draw" shot, it may even come backwards. But these small motions are due to the spin on the cue ball, and momentum is still conserved.

When billiard balls collide at a glancing angle momentum is conserved, but account must be taken of the various directions involved.



Conservation of momentum. The block of concrete absorbs the blow of the sledge hammer.

Balls made of inelastic material like putty or lead tend to stick together on collision. But momentum is still conserved with the MV of the two balls before impact equal to the MV after impact.

Conservation of momentum is sometimes of practical value. When you drive a nail into a thin wall you hold a heavy weight up behind in order to absorb the blow of the hammer and thus prevent the wall from giving under the impact. The massive weight moves very little even though it receives most of the momentum of the hammer.

Similarly, a circus strong man is able to withstand the mighty blows of a sledge hammer on his chest or stomach. A block of concrete is placed on his chest, apparently for the purpose of making a more impressive demonstration of strength. Actually the heavy block cushions the blow of the sledge hammer because its velocity of recoil is small.

The action of torpedoes, depth charges, and underwater mines is also, in a sense, an example of the conservation of momentum. The

surrounding mass of water recoils only a little at the instant of the explosion, while the relatively light plates of the ship hull or the submarine are driven rapidly inward. As you know, these devices are relatively ineffective unless they are exploded under water. In the case of a land mine, the earth itself acts as the massive stock of the gun, and the unfortunate tank is the less massive projectile.

IX. *Are Rocket Ships Feasible?*

The flight of a rocket is a particularly good illustration of the conservation of momentum. The rocket is propelled by the kickback of hot gases, which are formed by rapid burning of a propellant charge in the combustion chamber. The gas, though small in mass, emerges from the combustion chamber with terrific speed, and the rocket recoils in the opposite direction.

Nowadays in the comic strips and magazines we read about rockets streaking through empty space to Mars and the other planets. Are you one of those people who think that this is fantastic and impossible? Fantastic, perhaps, but, theoretically at least, entirely possible. Would it surprise you to learn that a rocket travels better in vacuum than in the atmosphere? The air is not necessary for the rocket gases to push against. In fact, air resistance exerts a retarding effect on the flight of a rocket. When man does succeed in navigating the vacant space outside the earth's atmosphere, it will presumably be with rocket-driven craft, for there is no other known method that would work at all.

Although no one has ever constructed a rocket for travel into space, much thought has been given to the problem. With the fuels that are now available, a rocket to carry a man clear outside of the earth's attractive field would have to weigh many tons, most of the starting weight being fuel. The best design is now believed to be a series of rockets, all attached together. Each rocket would carry all the smaller rockets as its pay-load. After the largest rocket has been burned out, its empty shell would be discarded and the next-largest rocket would be burned, and so on.

Needless to say, such a mammoth project is not likely to be started anytime soon. But if some much better propellant should be discovered, it might be a different story. You can see for yourself what is required. If the flight is to be made with less mass to throw away, each bit of the mass must be thrown out of the rear of the rocket with

higher speed. This means that the flame in the combustion chamber must be much hotter than can be achieved with present-day materials.

Perhaps Buck Rogers' space ships will never become a reality—certainly not for some time to come. But, as you know, rockets were very important weapons in the recent war. They ranged in size from the bazooka missile to the mighty V-2. And the development of rockets has continued apace since the war ended.

All kinds of jet-propulsion engines are similar to rockets in their action. Their forward thrust is a recoil from a blast of hot gases escaping backward through a nozzle. A jet-propulsion engine usually depends on getting the oxygen for its flame from the air through which it flies, while a true rocket carries its supply of oxygen along with it. We shall see more about all these *reaction motors* (as they are called) in Chapter Thirteen.

X. *What Is the Scientific Meaning of the Terms Work, Power, and Energy?*

Many words that we use in our everyday vocabulary assume a more precise and often a more limited meaning in the world of science. One of these is the term *work.*

Ordinarily we think of tasks such as studying, or washing dishes, or digging ditches, or even sitting at a desk in the office, as forms of work. In science, the term is much more restricted. Work is accomplished only when a force moves some object through a distance. You can do work by lifting a sack of flour; by shoving a box across the floor against friction; by heaving a ball down a bowling alley; or by cranking your automobile. You cannot do any work (scientifically speaking) by pushing an automobile that is stuck in the mud—unless the automobile moves.

Work is defined as the product of the force times the distance that the force moves some object:

$$Work = F \times D$$

In the English system of units, work is frequently expressed in *foot-pounds.* Thus, if you carry a 100-pound sack of flour up a stairway 20 feet high, you perform an amount of work equal to 100×20, or 2,000 foot-pounds. If you drag the same sack along the floor for a distance of 20 feet, and if the frictional resistance is 30 pounds, then you have done an amount of work equal to 30×20, or 600 foot-pounds.

On the other hand, if you simply carry the sack across the level floor, you do no work at all (after you have lifted it), because there is no resisting force. Except as it causes friction, the weight does not affect the work done in moving an object along the level at constant speed.

Power is the rate at which work is performed. It is equal to the work done, divided by the time it takes to do it.

$$Power = \frac{Work}{Time} = \frac{F \times D}{T}$$

Thus if you carried that sack of flour up the stairs in 10 seconds, you were working at the average rate of 2,000/10, or 200 foot-pounds per second.

The *horsepower*, a common unit for measuring power, is defined as 550 foot-pounds per second. You were developing a little more than a third of a horsepower in carrying the sack of flour upstairs. Incidentally, an average man is able to work steadily at the rate of about 1/10 horsepower when using his arms. In a spurt for a few seconds, however, a husky athlete can develop over 2 horsepower with his legs. Our legs are more powerful than our arms.

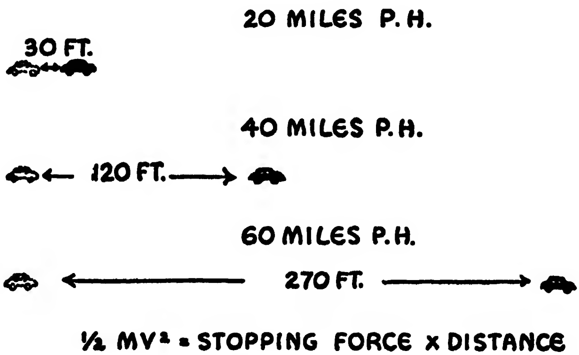
Perhaps you wonder whether the term *horsepower* really means what its name implies. Is it actually the rate at which a horse can do work? Yes, it is—approximately. In eighteenth century England, when stationary steam engines were first being sold for use in mines and elsewhere, the prospective purchasers naturally wanted to know how many horses the new contraptions could replace. So James Watt and his associates, who were selling the engines, measured the rate at which a draft horse could work, and they called this rate the *horsepower*. It turned out to be 550 foot-pounds per second.

One of the clumsy steam engines of Watt's day could replace only a few horses. By comparison, the power of modern engines is amazing. Think of the number of horses or men that would be needed to do the same quantity of work in the same time! Even low-priced automobiles now have a capacity of 90 horsepower packed into their small engines. Aeroplane engines occupying much less space than a single horse develop 1,000, even 2,000, horsepower. A single large steam engine may have as much power-capacity as 100,000 horses, or 1,000,000 men.

The last term to be discussed is *energy*. Scientifically speaking, energy denotes the stored-up ability to do work. There are many forms of energy—chemical energy, heat energy, electrical energy, to

name only a few. In mechanics, however, we are interested in two special kinds, *kinetic energy* and *potential energy.*

Potential energy is energy of position. When we compress or stretch a spring, we do work that is stored up in the spring as potential energy. We can recover the work when the spring is released. Similarly, work must be expended in pushing an automobile up a hill. This work goes into potential energy. We get the same amount of work out of the automobile when it rolls down the other side of the hill. In all these cases, it is not quite true that all the work expended can be recovered and used—friction, as we shall see later, takes its toll in these energy transactions.



Kinetic energy. The distance required to stop an automobile increases as the square of the speed.

Kinetic energy is energy of motion. Any moving object is able to do work simply because it is moving. The quantity of energy depends on the mass and the velocity. A 10-ton truck going 60 miles per hour has 10 times the kinetic energy of a one-ton automobile going the same speed. In this way kinetic energy resembles momentum (MV), since it is proportional to the mass of the moving object. But there is a difference. The truck going 60 miles per hour has not twice the kinetic energy of the same truck going 30 miles per hour, but four times as much. In other words, while momentum is proportional to the first power of the velocity, kinetic energy is proportional to the square of the velocity. Kinetic energy is defined as $\frac{1}{2}MV^2$. The factor "½" is introduced for mathematical convenience in working problems, and it need not concern us here.

The fact that kinetic energy is proportional to the square of the velocity is of practical importance in stopping a fast-moving vehicle such as a train or an automobile. The distance required for stopping is proportional to the kinetic energy; that is, to the square of the speed. Doubling the speed quadruples the stopping distance. Tripling the speed multiplies the stopping distance nine times. For example, if the brakes can stop your automobile in a distance of 30 feet when you are going 20 miles per hour, the stopping distance will be 120 feet at 40 miles per hour, and 270 feet at 60 miles per hour. For safety's sake, it is well to remember this.

Similar considerations show us one reason why gasoline consumption is so much greater for stop-and-go driving than for steady driving. Every time you attain a speed of 40 miles per hour, enough kinetic energy is stored up to carry the car perhaps a quarter of a mile along the level against normal frictional resistance. When you stop quickly, most of this energy is wasted in heating the brake drums.

XI. *Why Is Perpetual Motion Impossible?*

Would-be inventors who know little about scientific theories often waste much time and effort in devising elaborate "perpetual motion machines." None of these devices has ever worked, but the inventors keep on trying, nevertheless.

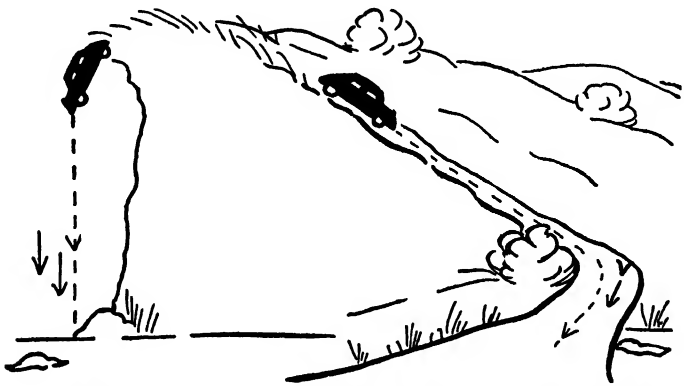
Thousands of experiments over a period of many years have convinced scientists that energy never appears out of nowhere; nor is it ever lost. It may be changed from one form into another, and it is frequently wasted for practical purposes; but the total energy of the universe remains constant. This important conclusion is known as the *Principle of the Conservation of Energy.**

If it is true that energy cannot be either created or destroyed, "perpetual motion machines" must ever be destined to fail. In order to get work out of a machine we must first put into it an equivalent amount of energy. As far as work and energy are concerned it is impossible to get something for nothing.

* According to Relativity Theory, energy may be transformed into matter, and matter into energy. This aspect of the theory has been proved correct in the laboratory by means of transmutation experiments. Also, the sun and the stars almost certainly derive their huge supply of energy from a gradual consumption of their mass. Therefore, the Principle of the Conservation of Energy must be modified in such cases by considering matter itself to be a form of energy.

In fact, on account of friction, we always get less useful work out of a machine than we put into it. In all mechanical devices friction takes its toll by wasting part of the energy in the form of heat. If, however, friction is small enough to be neglected, the total energy—potential plus kinetic—remains constant in accordance with the Principle of the Conservation of Energy.

For example, when a ball is thrown straight up into the air, its initial kinetic energy gradually changes into gravitational potential energy, until, at the top of its flight, the ball comes to rest momentarily and all of the energy is potential. As the ball falls, it regains its kinetic energy and loses potential energy. Hence the total energy is constant—there is merely a shift back and forth between the kinetic and potential forms.



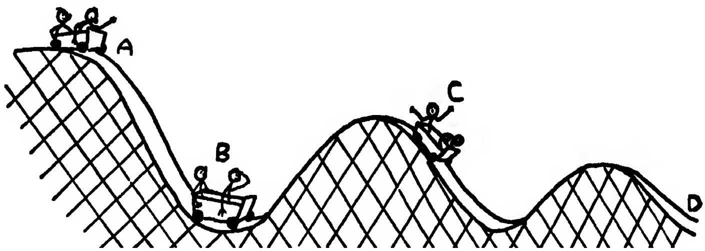
The automobile falling off the cliff and the one coasting down the hill will arrive at the bottom traveling the same speed (neglecting friction and assuming both cars start from rest).

You are familiar with other examples of the conservation of mechanical energy. Thus the potential energy of a wound clock spring changes into kinetic energy of the moving wheels (and eventually into heat through friction) as the spring unwinds.

The potential energy of an automobile coasting down hill changes to kinetic energy as the car picks up speed. Many people think that a heavy car coasts down hill faster than a light car, but this is not true. Neglecting friction, conservation of energy tells us that the speed of an automobile at the bottom of a hill must be the same no matter what the mass of the car. Furthermore, the kinetic energy, and hence the speed, depends only on the net change

in altitude (that is, on the vertical drop), and not on the length or shape of the incline. In other words, neglecting friction, the speed at the bottom will be the same whether the automobile drops straight down off a cliff, or whether it rolls down a long gradual incline—provided the initial heights are equal. In actual practice, however, friction usually modifies this conclusion. More energy is lost in friction when the car rolls down a long grade than when it goes down a short steep hill. So the speed at the bottom of the steep hill is greater.

The roller coaster of the amusement parks provides an excellent example of energy conservation. The car is pulled to the top of the



The roller-coaster illustrates the conservation of energy. (*A*) The energy of the car is all potential. (*B*) The energy is all kinetic. (*C*) The energy is partly potential and partly kinetic. (*D*) Friction has consumed most of the energy.

first long incline, and thereafter coasts under the influence of gravity. At the bottom of the hills the energy is kinetic; at the top it is mostly potential. The car could keep on going up and down indefinitely if friction did not gradually use up the energy and reduce the speed. Incidentally, that terrible sinking feeling in the pit of your stomach is caused by the rapid acceleration when the car is picking up speed on the downgrade. You feel the same sensation when a high-speed elevator first starts downward. At constant velocity, no matter how fast you are going, there is no such reaction. When a dive bomber pulls up at the bottom of a dive, the pilot experiences a more pronounced case of this same sinking feeling—not because he is traveling so fast, but because his velocity is changing so rapidly.

CHAPTER THREE

SOME SPECIAL KINDS OF MOTION

I. *Is Friction Good or Bad?*

Friction always manifests itself as a force that opposes motion. As we have seen, it causes waste in every engine and machine, by transforming mechanical energy into useless heat. Also, it wears away metal in the moving parts, making expensive repairs necessary. Engineers combat these losses in various ways. They reduce friction in the working parts by oiling the surfaces, by introducing roller or ball bearings, and by choosing the best materials for bearing surfaces. When necessary, they carry off the extreme heat of friction by means of circulating water and blasts of air. In all mechanical devices, friction in the moving parts is an unending nuisance.

But is friction always an evil?

Let us assume a hypothetical situation: you somehow suddenly find yourself sitting stationary in the center of a completely frictionless sheet of ice. What can you do to get off? No matter how you scramble or try to push yourself, you are helpless because there is no frictional resistance to push against. According to Newton's First Law of Motion, you are apparently destined to stay marooned where you are, forever. Evidently, friction is not always a bad thing. In this situation you would give your right arm for just a tiny little friction force.

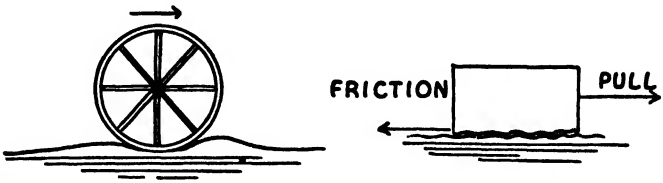
Of course, no such thing as a completely frictionless surface actually exists; and if it did, you could still get off without sacrificing your right arm. You would need only to remove your shoe and throw it; or for that matter, just spit! Conservation of momentum would then require that your body recoil in the opposite direction; and with nothing to stop you, you would keep right on sliding until you got back into the world of friction.

Without friction, this would be a strange universe indeed. We could not walk, nor even stand up; our clothes would fall off, because there would be nothing to hold the threads together; we should find it difficult to build houses, because the nails would fall out; screws and bolts would not hold, because they too require friction to keep

them in place; the hills would level out like water, because there would be nothing to hold the rocks and grains of sand together. Certainly, if friction is sometimes an evil, it is a very necessary evil. We should like to eliminate friction in the working parts of our machines, and at the same time retain it in the parts that must be fastened together by bolts, screws, or other means.

II. *What Are the Properties of Sliding Friction?*

The friction between dry sliding surfaces is caused chiefly by the interlocking of the microscopic humps and hollows that are present



Rolling friction is caused by the depression of the level surface; sliding friction by the interlocking of minute irregularities.

even on the smoothest surfaces. These projections must be sheared off or mowed down before one surface can move relative to the other.

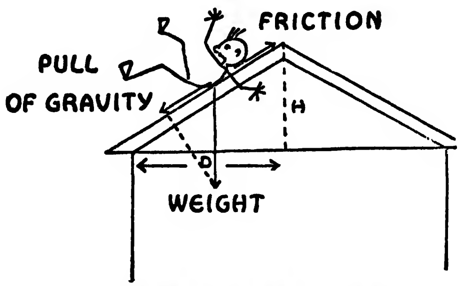
Experiment has shown that we can write down some approximate rules or laws governing sliding friction between clean dry surfaces. These rules are of interest, because they have practical importance. One rule states that greater force is required to start an object sliding than to keep it moving (along a level surface at constant speed) after it is started. We might expect this, because once the surfaces are in motion, the tiny irregularities are no longer firmly interlocked, but tend to hop over one another. It follows, too, that the force of friction should be nearly independent of the speed of the sliding object, once motion has begun.

A second rule states that for clean dry surfaces friction is proportional to the force pressing the surfaces together, but is independent of the area of contact. Thus the force required to push a brick across a level floor is the same whether the brick is lying flat or standing on end. But the friction will be doubled if a second brick is piled on top of the first one.

Friction varies between wide limits, but a third rule tells us that the friction between surfaces of unlike material is less than the fric-

tion between surfaces of like material. For this reason, bearing surfaces in machinery are usually made of dissimilar metals. Thus a steel crankshaft slides on a bronze (or babbitt) bearing surface. This rule, again, might be expected. The irregularities on two steel surfaces should be more alike, and therefore should interlock more firmly, than the irregularities of two unlike surfaces such as steel and brass.

If you ever have occasion to climb onto a roof or other sloping surface, you would be wise to have some idea ahead of time whether



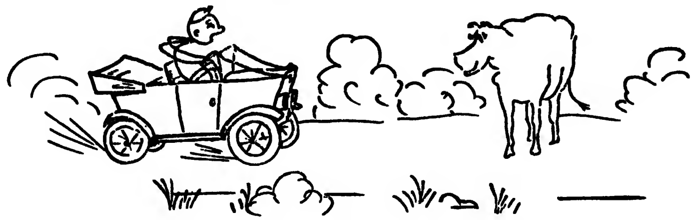
The unfortunate individual will slide off the roof if the pull of gravity is greater than friction.

the friction is sufficient to keep you from sliding off. Since one of the rules says that friction is less after you begin to slide than it is while you are stationary, the chances are all against ever stopping yourself if you once begin to slip. Lying flat on your stomach or back will not help, because friction is independent of area of contact.

The rules of sliding friction reveal some interesting facts about the skidding of automobiles. For instance, one of the rules tells us that on a dry road the friction between tires and pavement is independent of the area of contact. This means that the large balloon tires are no less likely to skid than are the old-fashioned small, hard tires. On wet or icy pavement, however, the rule no longer holds, and balloon tires are somewhat superior. Non-skid tread, too, possesses little advantage over smooth tread on hard dry roads; but some forms of non-skid tread help greatly to prevent skidding when the pavement is wet.

Incidentally, since friction is proportional to the weight, the minimum stopping distance (determined by friction between tires and pavement) is no greater for a heavy car than for a light car. The friction increases as the weight of the car increases.

When you apply the brakes in order to stop as quickly as possible in an emergency, you will do better not to step down hard enough to slide the wheels. Remember that the force of friction is greater



You'll stop quicker if you don't slide the tires!

before slipping begins than afterwards. Similarly, when you are stuck in mud or snow, you have a better chance of getting out under your own power if you let the clutch in very gradually and do not spin the rear wheels (second gear makes this easier). Once the wheels begin to spin, the friction between wheels and slippery surface is decreased. When you go around a slippery corner, it is better to step on the throttle just a little—enough so that the engine neither drives nor retards the motion of the car. The tendency to skid will then be a minimum.

III. *Is Streamlining Effective?*

In these days it seems that everything must be streamlined. Like the "daring young man on the flying trapeze," even our refrigerators and dining room tables look as though they were made to "float through the air with the greatest of ease." Frictional resistance of air and water is a matter to be reckoned with at high speeds. But aside from possible aesthetic value, one may doubt whether there is anything to be gained by streamlining a baby carriage.

It is found experimentally that fluid friction increases as the square of the speed. For example, air resistance is four times as great at 100 miles per hour as at 50 miles per hour. But the situation is even more serious than it seems. Power equals force multiplied by velocity.* Therefore, the power required to overcome fluid friction increases as the cube of the velocity. Compared to the power needed at 50 miles per hour, the power at 100 miles per hour is $(2)^3$, or 8 times as great.

* This relation comes about because, *power = the rate of doing work* $= F \times D/T$ (p. 31); but D/T = *velocity*. Therefore, *power* $= F \times V$.

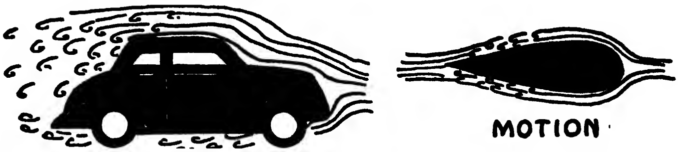
One can calculate from experimentally determined formulas that at 50 miles per hour an automobile requires 10 to 20 horsepower in order to overcome air resistance. Probably another 20 horsepower is needed to overcome the frictional resistance of the moving parts. Hence, at speeds up to 50 miles per hour, air resistance is not a vitally important factor unless the car is bucking a strong wind. But at 100 miles per hour, an old-fashioned unstreamlined sedan would need nearly 150 H.P. to overcome air resistance alone. A modern streamlined automobile might reduce this requirement to one-half of 150, or 75 H.P. Complete streamlining, if it could be achieved, would cut the power requirement to something like 15 H.P. One can conclude from this that an automobile designed to go much faster than 50 miles per hour should be carefully streamlined, if power and fuel are not to be wasted in overcoming air resistance. It is clear, too, that fuel consumption will always increase at high speeds, even with effective streamlining.

At still greater speeds, frictional air resistance becomes very serious, even with the best possible streamlined designs. Modern warplanes flying up to 500 miles per hour require at least 2,000 horsepower to overcome air resistance. The fastest commercial planes have been constructed with sealed, supercharged cabins so that they can fly at altitudes of several miles where the air is thin and resistance is greatly reduced.

At various times it has been reported in the newspapers and elsewhere that the deer fly is able to travel at the enormous rate of 800 miles per hour. The noted scientist, Dr. Irving Langmuir, ridicules this claim. He points out that at such a velocity the fly would encounter air resistance of more than three ounces, and its power consumption would be more than one-half horsepower. To supply energy at that rate, the fly would have to eat more than its own weight in food each second. Incidentally, the fly would become completely invisible at a speed considerably less than 100 miles per hour. Dr. Langmuir says that the deer fly actually goes about 25 miles per hour instead of 800. Because of air resistance, it is doubtful whether any insect ever flies as fast as 100 miles per hour.

All this brings up the question of the cause of fluid friction, and of the designs that reduce it to a minimum. You might think that resistance of this kind would be caused by a piling up (excess pressure) of the air or water in front of the speeding object. But this is not the case. Instead, the resistance is due to a partial vacuum

behind the moving object, with the result that the normal pressure in front produces a resisting drag. The partial vacuum in the rear is associated with the formation of whirlpools or eddies in the fluid when a body passes through at high speed. You have seen these turbulent eddies trailing behind a boat or other object moving rapidly through water. Similar, though invisible, eddies surround objects speeding through air.



Air resistance results from the formation of eddies accompanied by a partial vacuum behind the vehicle. The teardrop or similar streamlined design minimizes fluid friction.

Once we know the cause of fluid friction, it is not surprising to find that in streamlining, the shape of the rear end is much more important than the shape of the front. In this respect, sometimes in the past there has been considerable hokum in the streamlining of automobiles. Little is gained by streamlining the engine hood and body carefully, if at the time a spare tire, bumper, license plate, and other projections are mounted at the rear. Even small flat surfaces at right angles to the motion add greatly to the air resistance if they are located at the rear. In the front, flat surfaces make little difference.

One of the shapes that offer little resistance to motion through a fluid is known as the *teardrop* design. (An actual teardrop, incidentally, does not have this shape.) This is nearly spherical in front and tapers off gradually to a point in the rear. Many fish—bullheads, catfish, sharks, and the like—approach the teardrop form, and are thus very effectively streamlined. Obviously, in building automobiles, trains, or even ships, the wheels and other gear make it difficult to realize a true teardrop shape. In any case, flat surfaces in the rear should be eliminated and the cross-section area of the vehicle should be made as small as possible. But even the best designs will do no more than reduce the frictional force to a few per cent of the resistance of a flat surface of the same area. The eddies and vortices that cause the trouble cannot be eliminated completely.

IV. *What Is a Machine and What Does It Do?*

A machine is a mechanical device which serves to apply force or power more conveniently or to better advantage than would otherwise be possible. If we are willing to accept this rather comprehensive definition, we may list as elementary machines a number of simple devices, many of which have been known to man from prehistoric times. Among these aids-to-doing-work are levers, pulleys, gears, inclined planes, wheels, shafts, and axles. As a matter of fact, when you stop to think about it, all machines, no matter how complicated, are compounded out of just these simple devices in their various forms. To understand the action of any machine we need do no more than study its individual parts.

One of the commonest of elementary machines is the *lever.* We use a crowbar to pry loose a boulder; or we use the claw of a hammer

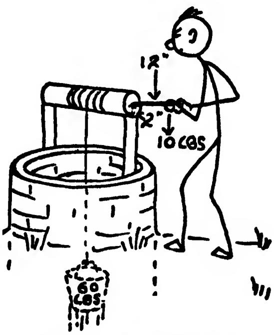
A simple machine. A small force exerted at one end of the crowbar results in a large force at the boulder.

to pull a nail; or we use a knife to pry up the lid of a can. In each of these cases, we apply a comparatively small force, with the result that the lever exerts a very large force. The ratio of these two forces is called the *mechanical advantage* of the machine. You recall from our discussion of the see-saw that the opposing torques about the pivot or fulcrum must be equal and opposite—a small force at a large distance from the fulcrum balances a large force at a small distance.

You should not think that we get something for nothing, just because a device like a crowbar converts a small force into a large force. Mechanical advantage refers to a gain of force—not to a gain of power or energy. In fact, on account of friction, we always lose energy; and even if friction may be neglected, the energy output is no more than equal to the input. To compensate for the gain in force, we are obliged to move our end of the crowbar a long distance, while the boulder moves only a tiny distance. The greater

the force exerted by the lever, the smaller is the displacement of the boulder.

The statements just made apply equally to all kinds of machines. Thus a *crank* (or its equivalent, a wheel and axle) makes possible a very large force at the small central shaft, with a comparatively small force applied at the rim. We use a knob to open the door, a wrench to tighten a bolt, or a windlass to raise a bucket of water out of the well. Equality of torques obviously requires that the mechanical



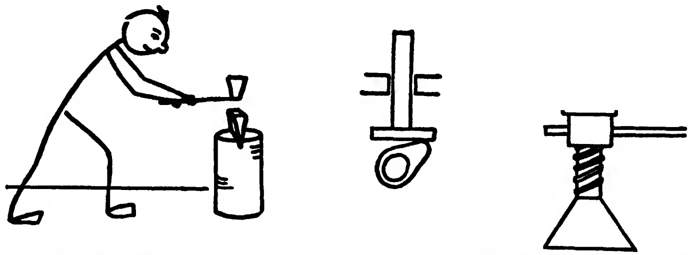
A windlass. The mechanical advantage of this particular machine is equal to 6.

advantage be equal to the radius of the large wheel (or length of the crank handle) divided by the radius of the axle. For example, a force of 10 pounds exerted at the rim of a wheel of radius 12 inches, results in a force of 10×6, or 60 pounds at the axle of radius 2 inches. The mechanical advantage is equal to 6. Sometimes we prefer to sacrifice force in order to gain speed; that is, a small axle drives a large wheel, as in the case of the rear axle and wheels of your automobile. Under such circumstances, the mechanical advantage might be called a mechanical disadvantage. At any rate, it is less than unity.

The *inclined plane* is another simple machine of widespread application. Cams, wedges, knives, ploughs, and all types of screws operate on the principle of the inclined plane. The mechanical advantage is often very great. For example, in splitting a wooden log with a steel wedge, the blow of a sledge hammer may produce a force of many tons. A few pounds applied to the lever of a jack-screw (such as you use to jack up your automobile to change tires) will lift a weight of several hundred pounds. Usually, these inclined-

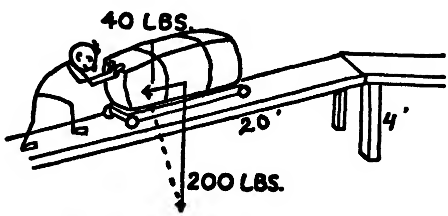
plane devices are inefficient because of the large frictional forces. Nevertheless, they are very effective in attaining the desired result.

The principle of the inclined plane is simple: if a farmer hoists a 200-pound bale of hay, for example, directly onto a platform, a lifting force of 200 pounds is required; but if he slides the bale up



Simple machines based on the principle of the inclined plane: wedge, cam, jackscrew.

an incline, he need apply only enough force to overcome the component of the weight tending to pull the bale down the inclined plane. This component is a fraction of the total weight equal to the ratio of the height of the plane to its length. Thus, to raise the 200-pound bale onto a platform 4 feet high, with the aid of a 20-foot

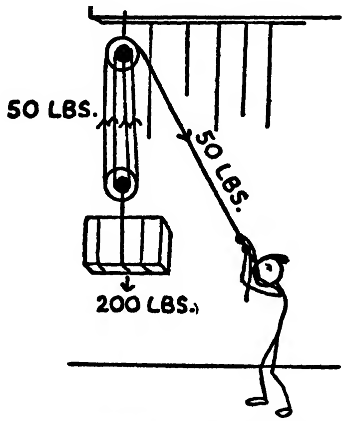


The inclined plane reduces the required force from 200 to 40 pounds. Mechanical advantage: 200/40, or 5.

incline, only $4/20 \times 200$, or 40 pounds push up the plane is required. To this force, the frictional resistance must, of course, be added. Neglecting friction, a mechanical advantage of 200/40, or 5, is attained.

Many different gear, chain and sprocket, and pulley devices are employed to transmit and apply power. In all of these, the mechanical advantage depends on the relative size of the two gear or pulley wheels that are connected together. Thus, the ordinary bicycle drive has a mechanical advantage considerably smaller than

unity, because the pedal sprocket has more teeth than the rear wheel sprocket. The wheels therefore revolve several times for each revolution of the pedals. Force is sacrificed for speed. On the other hand, an automobile engine makes several revolutions for each revolution of the rear wheels. Even in high gear, the ratio is something like 4 to 1. In the lower gears it is much greater. So-called "high-speed" engines make more revolutions than "low-speed" engines for each turn of the wheels. A high-speed engine gives a car greater pickup, and more power on the hills; but the low-speed engine supposedly wears longer because it makes fewer revolutions in a given driving distance.



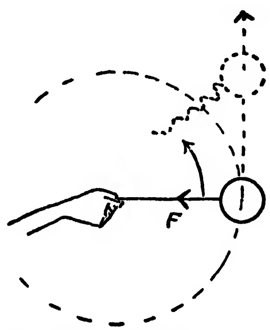
Block and tackle. Each of the ropes supports one quarter of the weight. Mechanical advantage: 200/50, or 4.

Combinations of several pulleys, such as may be found in the *block and tackle,* are convenient for lifting heavy weights. If a weight is suspended by a single rope slung over a single pulley, there is no gain in force or speed. The pulley serves merely to change the direction of the applied force—you pull down instead of up to lift a weight. But with a block and tackle, the weight is supported by a number of ropes leading upward from the lower block of pulleys. Each of these ropes carries the same fraction of the load. Neglecting friction, the force required to lift the object by pulling on the free end of the rope is equal to that fraction of the weight supported by each rope. Therefore, in general, the mechanical advantage is equal to the number of ropes leading upward from the lower pulley

block. If a 200-pound bale of hay is supported by a 4-rope pulley system, a farmer need pull with a force of only 200/4, or 50 pounds (plus a little extra for friction) to lift the bale into his hayloft. But if the bale is to be lifted 10 feet, the free end of the rope must be pulled through a distance of 4×10, or 40 feet. As usual, speed is sacrificed for the sake of increased force.

V. *What Is Peculiar About Motion in a Circle?*

We are so accustomed to wheels of all kinds that most of us never stop to think that circular motion is by no means a normal state of affairs. It exhibits many interesting peculiarities. In fact, the most difficult problems in mechanics deal with various forms of motion in a curve.



A ball whirled on a string is pulled in a circle by the force *F*. If the string breaks, the ball flies off in a straight line tangent to the circle.

No doubt you have whirled a stone or a ball at the end of a string and have felt the pull outward on your fingers. Likewise, when rounding a sharp corner in an automobile, you have felt yourself thrown against the outside of the seat. In connection with such experiences, the term *centrifugal force* probably comes to your mind. You think of the tendency of a body rounding a curve to fly outward into space.

Actually, there is no tendency to fly outward—if, by outward, you mean out along the *radius* of the circle. If you let go of the string, the whirling ball will fly off in a straight line along the *tangent* of the circle. Newton's First Law of Motion says that a body keeps going at constant speed in a straight line unless there is a force to change its speed or *direction* of motion. In the case of the ball rotating at the end of a string, there is no change of speed. Evidently,

then, the string pulls on the ball only for the purpose of making it go in a circle. This force, which pulls a body around in a circle, is called the *centripetal force.* It acts at right angles to the direction of motion, and causes a change in the direction of the velocity.*

But what, then, is the centrifugal force that we commonly speak about? It is the equal and opposite reaction to the centripetal force (Newton's Third Law). In other words, it is the pull that you feel on your finger when you hold on to the string which is attached to the whirling ball; or it is the force with which you yourself push against the seat of the automobile going around a corner. On the other hand, the centripetal force is the push of the seat against you. If the seat suddenly gave way, the centripetal force would no longer be available, and you would shoot off on a tangential straight line. The automobile would continue on around the curve without you.

If you really want a clear understanding of circular motion, I cannot stress too strongly this distinction between centripetal force and centrifugal force. Confusion about this matter has given rise to widespread misconception. Even technical books sometimes contain inaccurate or loose statements which may lead the reader to believe that there is a force pulling outward on a rotating body; and that the body will therefore fly outward radially if it is released. Let me repeat that the actual pull on a rotating body (the *centripetal force*) is directed inward toward the axis. Without this force, the body would no longer go in a circle—it would fly off in a straight line on a tangent to the circle. The outward pull (the *centrifugal force*) acts on the axis at the center—not on the rotating body. As a further illustration of these facts, you will recall that drops of water fly off of a rotating wheel tangentially in a straight line—not outward radially. The same thing is observed in the case of sparks shooting from an emery wheel or a pin wheel. The sparks are simply glowing bits of matter which have been loosened from the wheel and are therefore no longer forced to follow the wheel in its circular path.

Since the centripetal force varies with the mass, centrifuges and cream separators are very effective in sorting out liquid materials of different density or specific gravity. Milk, placed in the whirling vessel of the machine, soon separates, with the dense skim milk

* If it seems strange to you that there can be acceleration without increase or decrease of speed, remember that velocity is a vector. A change in the direction of the velocity is just as much an acceleration as a change in magnitude.

(mostly water) going to the outside, and the less dense cream gathering at the center. This process is completed in a small fraction of the time required for separation to take place in a stationary pan under the influence of gravity.

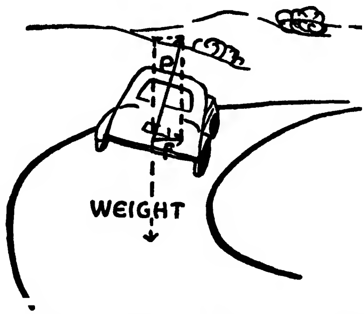
In biological and chemical laboratories, centrifuges are useful for separating heavy molecules or bacteria from light ones, particularly when ordinary chemical methods of separation are ineffective or would destroy the products. Some of these centrifuges (usually called ultra-centrifuges because they spin so fast) rotate on a cushion of air and are driven by jets of compressed air playing against the outer surface. These machines have been spun at a rate of more than 20,000 revolutions per second—200 times as fast as an automobile engine traveling at high speed. The centripetal force is millions of times as great as the force of gravity (the weight); and sometimes solid steel rotors, only an inch or so in diameter, blow up and shatter into bits because the tensile strength of the steel is insufficient to withstand the tremendous stress.

If you happen to be an aviator, and have ever looped-the-loop, you are probably aware that a strap to hold you in the plane was unnecessary, even when you were upside down at the top of the loop. If you have never been a stunt flyer, you have at least whirled an open pail of water over your head in a vertical circle, and have found that the water did not spill out if the pail was moving fast enough. But if the speed at the top of the loop is so small that the required centripetal force is less than the weight, then the aviator or water, as the case may be, will fall out.

When an automobile goes around a curve, friction between tires and pavement supplies the necessary centripetal force. If the force of friction is insufficient, the car skids. Banking of the road helps to prevent skidding, because the sidewise push of the road on the car then supplies some of the centripetal force. In fact, if the road is banked too sharply, there is a tendency to slide inward rather than outward. But the greater the speed and the sharper the curve, the steeper the slope should be to prevent skidding. Banked curves are especially important in the case of railroad tracks. Without banking, the wheel-flanges and tracks would soon give way under the terrific strain of furnishing all the centripetal force for high-speed trains.

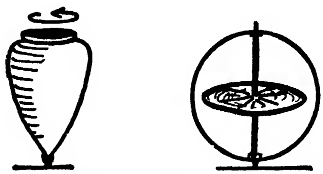
The ultimate in banked curves is attained at certain amusement parks where intrepid performers ride motorcycles on sheer vertical

walls inside a cylindrical structure that looks much like a huge barrel with a rounding bottom. When the motorcycles are going fast enough they can climb onto the vertical walls, and friction keeps them from falling. The body of the rider is practically horizontal.



Forces on an automobile rounding a banked curve. The horizontal component of the push-of-the-road P supplies the centripetal force F.

The mention of motorcycles raises the whole question of the equilibrium of moving and rotating bodies. Why is it that a motorcycle or bicycle rider can maintain his balance when his machine is moving, but not when it is standing still? Why does a spinning top or gyroscope stand upright without falling over? Such questions



A top and a gyroscope. Why do they remain upright while spinning?

are not easy to answer. In fact, advanced mathematical treatises on mechanics deal very largely with these and related problems. With respect to the top and gyroscope, perhaps it is sufficient to say that the proper interpretation of Newton's Laws of Motion reveals that the axis of a rotating body has an inherent tendency to maintain its original direction. The rotation causes the body to resist any effort to change that direction. Force pulling on the axis causes the body to move (or *precess*) but, strangely enough, the motion is at right angles to the applied force. If you have played with a toy gyroscope, you have perhaps noticed how the frame perversely jumps out

sideways from under your finger when you try to tilt it in a new direction.

Gyroscopes have proved valuable in many practical applications. Thus, large massive gyroscopes have been used in an effort to stabilize ships and prevent rolling. They likewise serve to balance monorail cars. As the name implies, these cars run on a single rail and are kept upright, even when stationary, by the action of the gyroscope. In such applications, the axis of the heavy gyroscope wheel must be at right angles to the direction of motion of the ship or car. Gyroscopic effects also prevent rifle bullets and gun projectiles from tumbling end over end during flight. Spiral grooves cut in the barrel of the gun start the projectile spinning rapidly; and this rotation keeps the nose pointed in the direction of flight, thus preventing wobbling and minimizing air resistance.

Because of the rotation of the earth, the axis of a carefully balanced gyroscope tends to set itself parallel to the earth's axis. Nowadays, gyro-compasses are almost universally used on the larger ships. The gyro-compass has the advantage of always pointing toward the true geographic north, and it is not subject to local magnetic variations. On the other hand, its mechanism is complicated and delicate, and can easily get out of adjustment. It is necessary, therefore, to keep two or more magnetic compasses on hand as standbys, and to check the gyro-compass against these occasionally.

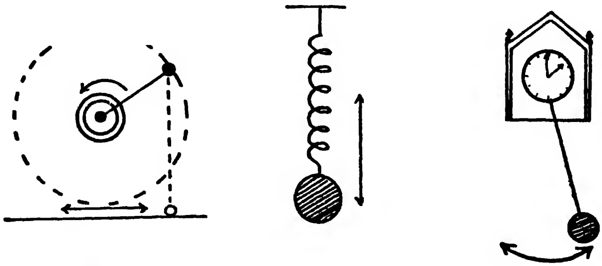
VI. *What Are the Characteristics of Vibration?*

Let us now turn to another important and interesting type of motion; namely, vibratory motion. A clock pendulum swinging to and fro, a bob vibrating up and down on the end of a coil spring, the oscillating balance wheel of a watch—all these are examples of bodies performing vibratory motion. Other examples, as we shall see in Chapter Eleven, are the vibrating strings and air columns in musical instruments.

To understand these motions, we shall examine one of the simplest cases, the bob hanging on the end of the coil spring.

Suppose you take hold of the bob and pull it downward, stretching the spring. You will find it is necessary to pull harder and harder, the farther the spring is extended. The force required to hold the bob down a given distance below its natural position, or rest position, depends on the stiffness of the spring.

Now, if the bob is released, it will be accelerated upward by the force of the stretched spring, and will move faster and faster upward until it reaches its rest position, and then will continue upward beyond the rest position, more slowly all the while, compressing the spring as it rises. Finally it stops, and reverses its motion, traveling downward with increasing speed until it passes through its normal



A B C

Examples of simple periodic motion. (*A*) Shadow of a revolving crank handle. (*B*) Bob vibrating on a coil spring. (*C*) Clock pendulum.

position, and then slowing to a halt as it stretches the spring once more. These up-and-down motions are repeated again and again, the length of path decreasing because of friction, until the vibration has died away.

It is easy to see how this up-and-down travel occurs, if we recall, from Newton's Second Law of Motion, that the acceleration of the bob at every instant is equal to the force with which the spring pulls up or pushes down on it, divided by the mass of the bob. The force is upward so long as the spring is stretched, and the bob is therefore accelerated upward, and gains upward speed. The bob passes at top speed through the central equilibrium position, where the spring is neither stretched nor compressed, and then loses upward speed as it is accelerated downward by the compressed spring. The accelerations are greatest at the ends of the path, where the spring is most stretched or compressed; the speed, on the other hand, is zero at these points, and is greatest at the central position where the force and the acceleration are both zero.

The energy situation is much the same as in the case of a roller coaster. At the ends of the vibration path, where the bob is at rest, all the energy is stored up in the spring as potential energy. At the central position, where the spring is neither stretched nor compressed, all the energy is stored up as kinetic energy in the motion

of the bob. In between the ends and center of the path, the energy is partly kinetic and partly potential. As the energy alternates between these two forms, friction continually abstracts a fraction of it, and the vibration finally stops.

The other cases of vibratory motion we mentioned can all be discussed in this same way. The clock pendulum, for example, is higher at the ends of its swing than in the center, and the force of gravity accelerates it toward the lowest point, just as the force of the stretched spring accelerates the bob upward.

Many cases of vibratory motion—all those we have mentioned—have in common one very interesting and useful property: the *period* (time for one complete vibration) is completely independent of the amplitude (half the total path traveled), if the amplitude is not too large. In other words, the clock pendulum makes the same number of swings in a minute when it is swinging through a short arc as when it is swinging through a larger arc—provided the arc is not too large. The period of the bob on the spring depends only on the mass of the bob and on the stiffness of the spring. A heavier bob vibrates more slowly than a light one. Likewise, the frequency is lower if the spring is weaker.

The fact that the frequency is unchanging, no matter what the amplitude (within limits) is a fortunate property of these vibrations. For example, in the case of musical sounds, the pitch (which depends on the frequency) does not change with the loudness (which depends on the amplitude), unless the sound is very loud indeed. Likewise, the color of light is independent of its intensity. The study of sound and of light would be much more difficult if this independence were not true.

In the case of the clock pendulum swinging with small amplitude, the time in seconds for a swing from one side to the other is given by the formula:

$$T = 3.14\sqrt{l/g}$$

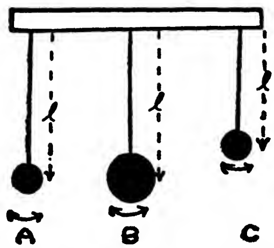
You will note that the time depends on the square root of two quantities: the length of the pendulum, l (feet), and the acceleration of gravity, g (approximately 32 feet per second per second). It depends on nothing else. One can easily calculate that the so-called *seconds pendulum* (a pendulum that swings from one side to the other in one second) is about 3.25 feet in length.

If your clock pendulum gains or loses time, the formula tells you

what to do to correct it. A gain means that the pendulum oscillates too rapidly—its period is too small. Therefore, the pendulum must be lengthened. If the clock loses, the pendulum must be shortened to make it swing faster.

What would happen to your pendulum clock if you took it up on top of a mountain where the acceleration of gravity is less than at sea level? You can readily reason out the result. If g is small, T is large, and the clock will lose time. As g becomes smaller, the length l must be decreased correspondingly to keep the period constant.

Since the period depends on the acceleration of gravity, pendulums are used to measure the value of g at various points on the



The simple pendulum. Pendulums *A* and *B* vibrate with equal frequency; *C* vibrates more rapidly.

earth. The time of swing and the length of the pendulum can be determined very accurately; the value of g is then easily calculated. Aside from general scientific purposes, such determinations have a practical value in prospecting for oil. One of the standard geophysical methods for locating oil involves accurate measurements of the variations in g over the region to be tested. Near a subterranean oil pool, the density of the earth beneath is usually somewhat different from that in the surrounding territory: and the force of gravity is changed just a tiny bit. The method is by no means infallible, but it furnishes one of the indications of oil.

VII. *What Is Gravity, and What Are Its Effects?*

Besides the effect on the period of a pendulum, we have seen that the force of gravity (and hence the acceleration of gravity, g) plays an important role in many common phenomena of a mechanical nature. The rate at which a body falls depends on the value of g. The weight of a body is nothing but the pull of gravity toward the

earth. Mass is an inherent, invariable property of matter which has to do with inertia; but weight varies from place to place on the earth, depending on the force of gravity. For example, if you weigh 200 pounds at the north pole, you would weigh only about 199 pounds at the equator.* You weigh slightly less on top of a mountain than at sea level.

This variation in gravity is one reason why scales that contain springs are less reliable for accurate weighings than are those that make use of a system of levers to balance masses against each other. On the moon, your weight (that is, the pull of gravity) would be only 1/6 as much as on the earth. But your mass, as determined by the type of scales which contain no springs, would be the same as on earth. Masses balance each other, no matter how large or how small the pull of gravity on them. If you weigh 180 pounds on the earth, your mass would still be 180 pounds on the moon. But your weight, or the force of gravity, as measured by a spring balance, would be only 30 pounds.

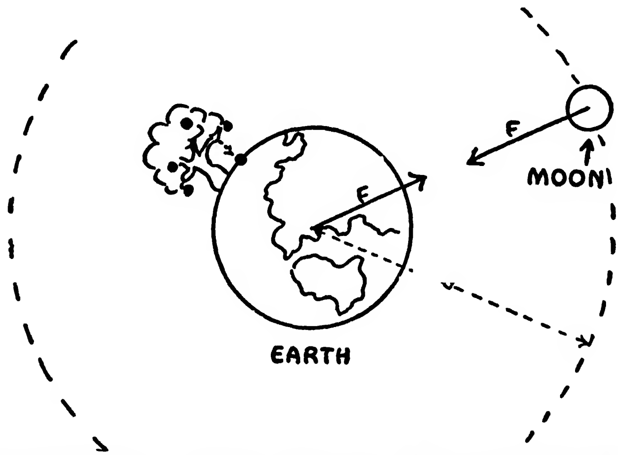
Before the time of Sir Isaac Newton, apparently no one ever suspected that the motion of falling bodies had anything in common with the motion of the moon and the planets. Aristotle, as well as most of the other learned men of Ancient Greece and Rome, believed that the earth was flat and was located at the center of the universe. This belief persisted through the Middle Ages. But before Newton was born (1642) it was commonly accepted, at least among educated people, that the sun, and not the earth, was the center of the solar system. The calculations of Kepler (1571–1630), based on the painstaking observations of the Danish astronomer Tycho Brahe, had shown that the paths of the planets are not exactly circular, but are slightly elliptical in shape. For instance, the earth is some three million miles nearer the sun in winter than in summer.

Knowledge of *how* the planets move was an important advance in science. When Newton proposed his spectacular Law of Gravitation, he made another tremendous step forward in the correlation of physical phenomena. The idea is said to have flashed into his mind as he sat in the garden and watched apples falling from a tree. It

* This difference is due partly to the flattening of the earth at the poles, with the result that an object at the pole is slightly closer to the center of the earth, and is therefore attracted more strongly by gravity. Most of the difference, however, is due to the centripetal force required at the equator to keep things rotating with the earth. This centripetal force is supplied by gravity, and the measured value of the weight is thereby reduced at the equator.

occurred to him that possibly all objects in the universe are attracted to one another by some mysterious force; that the same attraction is responsible not only for the motion of a falling apple, but equally well for the motion of the planets around the sun and of the moon around the earth. By mathematical calculation, Newton proved that the orbit of the moon is just what it should be on the basis of his proposed law of force.

The Universal Law of Gravitation may be expressed as follows: *Any two objects in the universe are attracted to each other with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them.*



The force of gravitation. *F* keeps the moon revolving around the earth and causes an apple to fall to the ground.

This means that the greater the mass of an object, the greater the force with which it attracts another body; also, the greater the distance between their centers of gravity, the less the force of attraction. Thus, when we climb a mountain and get a little farther away from the center of the earth, our weight becomes slightly less than at sea level.

The Law of Gravitation is universal, but we do not notice the force between two ordinary objects because the attraction is so small. Thus, two cannon balls, one foot apart and weighing 100 pounds each, attract each other with a force of only five millionths of an ounce. But with the body as huge as the earth or the moon, it becomes a different story. The attraction toward the earth accounts

for such phenomena as weight and the motion of falling bodies. Gravitation also explains the ocean tides on the basis of lunar and solar attraction. The moon is so much closer to the earth than is the sun, that it has more tidal effect, even though its mass is smaller. The highest tides (spring tides) occur when the sun and the moon are both on the same side of the earth, and thus act together.

With such a great force of attraction, you might suppose that the moon would fall into the earth, just as an apple drops from a tree. What prevents such a catastrophe? Similarly, what keeps the earth from falling into the sun? With your knowledge of mechanics, you should be able to answer these questions. If there were no force of gravitation, Newton's First Law of Motion would require that the moon and the earth both fly off into space along a straight line. But gravitation supplies just the centripetal force necessary to hold the planets in their circular (or elliptical) orbits.

How the planets got started moving in their orbits in the first place is a mystery that can be solved only when we know more about the origin of the solar system. Some astronomers think that the planets were once a part of the sun, and were pulled away by the gravitational attraction of another star passing close by. At any rate, it seems probable that the formation of the planets and their moons was an unusual accident, and that few if any of the billions of stars in the heavens have similar satellites. It is possible, in other words, that the conditions of atmosphere, temperature, and humidity, that are essential for the earthly forms of life, are duplicated nowhere else in the universe. But this is largely mere speculation.

CHAPTER FOUR

THE BEHAVIOR OF SOLIDS, LIQUIDS AND GASES

I. *What Is Matter?*

Throughout the history of the world, the question of the ultimate nature of matter has received much attention from philosophers and scientists. Anaxagoras (500–428 B.C.) claimed that matter is made up of minute particles which he called seeds. But Anaxagoras was a radical in this and other respects, and he was soon exiled for his views. Most of the Greek philosophers believed that there are four essential elements—fire, air, water, and earth—from which all things are made. Aristotle (384–322 B.C.) added a fifth element—a celestial element—which he called ether. Aristotle and the majority of his contemporaries believed also that matter is continuous—that it could be subdivided into smaller and smaller bits without limit.

In the Middle Ages, the atomists and alchemists were inclined to break away from the tradition of Aristotelian infallibility, and assume that matter is composed of particles, called atoms, which cannot be further subdivided. By rearranging and changing the proportions of the atoms of the elements—fire, air, water, and earth—any substance, they thought, could be changed into any other substance; hence the many dark and mysterious schemes for transmuting the base metals into gold.

The alchemists never quite succeeded in their efforts, and their assumption that all matter is made of fire, air, water, and earth, gradually became discredited. Their experiments, and the work of the chemists who followed them, showed the way to a more useful theory, one that was clearly stated by the English chemist, John Dalton (1766–1844), and is still accepted today. Matter, we now believe, is made up of atoms of the ninety-two chemical elements. All the atoms of a given chemical element—aluminum, for example—are alike, and are different from the atoms of any other element, such as oxygen or copper.

For nearly fifty years after Dalton's death there was little need tc wonder what atoms are made of, and how they differ from one element to another. The physicists, studying the behavior of gases,

found that the atoms acted like tiny indivisible grains of matter, possibly spherical in shape, and elastic like billiard balls. The chemists, who studied the compounds that are formed when atoms of the different elements get together into molecules, had to imagine that each atom has little hooks (or something of the sort) by which it can be attached to other atoms. But neither group had any particular reason to worry about the internal construction of an atom, nor any good basis for a theory about what atoms are like inside.

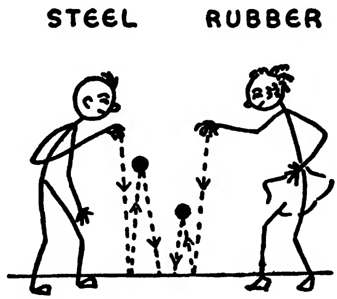
Therefore it was something of a shock to the scientists of the twentieth century when evidence began to accumulate, showing that atoms are made up of various combinations of electrons and protons, and are actually filled mostly with empty space. Ordinary chemical reactions simply had not been drastic enough to produce these new effects. High-powered radiation and electrical agents are needed. Nowadays, with the aid of high-speed atomic particles, we can even smash to pieces the nuclei of the atoms, and thereby transmute one element into another. The dream of the alchemists has been realized; but the efficiency of the transmutation process is very low.

But more practical questions await our immediate attention. In the first place, how shall we classify the various forms of matter? It is customary to distinguish between solids, which have a fixed shape and volume, and fluids, which flow and freely change their form. Fluids are further subdivided into liquids, which are constant in volume, and gases, which can be readily compressed or expanded.

This classification is not always satisfactory because, with sufficient provocation, solids change their form just as do fluids. Thus, a lead bullet, which ordinarily seems pretty solid to us, smashes flat on impact with a steel plate. Even the steel plate may be dented or pierced, and hence deformed, by a bullet made of steel. And how would you classify butter, axle grease, or pitch? Soft butter may be considered either a solid or a semi-liquid. Cold pitch normally appears to be solid; but if left to itself, it will gradually flow and, after some days or weeks, will assume the shape of the vessel in which it is placed. We know that even wooden beams may sag permanently—especially if they are allowed to become damp while subject to continuous strain.

A springy material like rubber or steel returns to its original shape after being deformed—provided the strain has not been excessive or greatly prolonged. Rubber, of course, can be stretched much

farther without breaking than can steel. But you may be surprised to learn that steel is more perfectly elastic than rubber, because it returns to its original shape with smaller loss of energy; that is, with less internal frictional heating. Thus, a steel ball, dropped onto a steel surface, will rebound higher than will a rubber ball dropped



Steel is more elastic than rubber! A steel ball rebounds higher than a rubber ball from a hard surface.

from the same height. Ivory billiard balls are also very elastic; the ordinary composition pool balls much less so. A lead ball or a putty ball will rebound scarcely at all, because lead and putty are quite inelastic, and are likely to be permanently deformed by any impact.

Though liquids are characterized by their ability to change their shape, some liquids, such as honey, molasses, and thick oil, flow very slowly. We say that these liquids are highly *viscous.* If left to itself long enough, a viscous liquid will conform eventually to the shape of the vessel in which it is placed; but the process takes a long time.

Viscosity usually increases rapidly as a liquid becomes colder. Thus, the oil in your automobile crankcase is stiff on cold mornings, and the self-starter has difficulty in cranking the motor. The Society of Automotive Engineers (S.A.E.) ratings for motor oil are based on viscosity. A light winter oil of S.A.E. rating 10 or 20 is much less viscous than is a heavy summer oil of rating 40 or 50. Since the lubricating properties of an oil depend partly on its viscosity, a good oil must hold its "body" at high temperatures, and not become too thin and watery. In other words, the viscosity of the oil should not change too greatly as the motor heats up. Oils containing a large proportion of wax are particularly bad in this respect, because the viscosity of wax decreases rapidly at high temperature.

II. *What Are Surface Tension and Capillarity?*

Such properties of matter as elasticity and viscosity depend on the forces between individual atoms and molecules. The forces of attraction between atoms may be very great. For example, it requires nearly 50 tons force to pull a one-inch bar of hard steel apart. A force of 15 tons stretches or compresses such a bar only one one-thousandth of its length. The detailed nature of these interatomic forces is none too well understood; but the attractions and repulsions are probably electrical in origin.

The attractive force between like materials is called *cohesion;* between unlike materials, *adhesion.* Normally, cohesive forces are stronger than adhesive forces—but not always. For example, the adhesive forces between good glue and wood are greater than the cohesive forces. For this reason, when pieces of wood are glued together, one should always make the layer of glue as thin as possible. Then the wood will splinter and give way before the glued surfaces can be pulled apart.

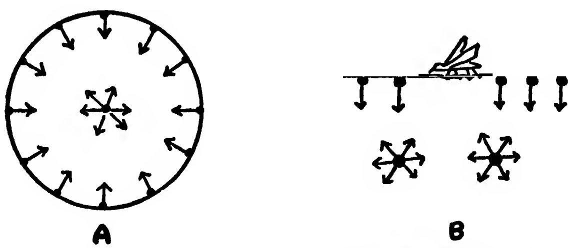
Water or any other liquid can wet a solid surface such as glass, because the adhesion between water and glass molecules is greater than the cohesion between water molecules. The glass molecules tear water molecules away from their neighbors. On the other hand, if the cohesive forces are greater than the adhesive forces, the liquid does not wet the solid surface. Thus, water runs off a duck's back because the adhesive force between water and oily feathers is weak.

Since atoms and molecules usually attract one another strongly, you might wonder why any two solid objects do not stick together when they come into contact. Why, for instance, do two pieces of iron fail to attract each other appreciably when they are pressed together? Perhaps the answer is obvious. On the relatively rough surfaces, very few spots actually make contact; most of the atoms on one surface are too far away to attract the atoms on the other surface. As a matter of fact, if steel blocks are ground very, very flat, cohesive forces become appreciable, and two blocks an inch in diameter will stick together so firmly that a force of several hundred pounds is required to separate them. When iron is melted, as in welding, the atoms are brought close enough so that they hold together very firmly.

Adhesive and cohesive forces in a liquid give rise to the important phenomena of *surface tension* and *capillarity.* Can you explain, for

example, why small droplets are spherical? why oil rises in a lamp wick? how insects are able to walk on the surface of the water without getting their feet wet? The answer in each case is surface tension. But let us see how it works.

A molecule located in the center of a body of water or other liquid is attracted equally in all directions by its neighboring molecules. There is no unbalanced pull in any one direction. But the molecules on or near the surface are attracted downward by their neighbors below, without any compensating force from above. As a result, every molecule that can do so gets inside, and the liquid resists any effort to increase its surface, which would mean increasing the number of molecules on the surface. It is as though the surface of the water were covered with a stretched skin or membrane that tends to contract and draw the whole volume of water into as small a space as possible. If the volume of water is great, the surface tension forces are defeated by the forces of gravity; but in the case of tiny droplets, surface tension wins out and the drops are



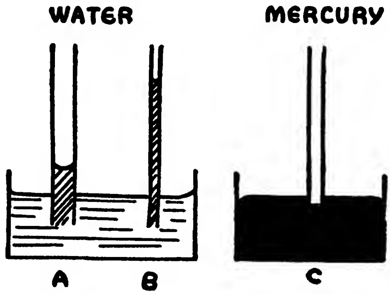
Forces acting on water molecules. Surface tension keeps the droplet *A* spherical, and enables the insect to walk on the surface of the water in the vessel *B*.

drawn into a spherical shape. When you fill a glass to overflowing, the liquid does not spill out even though the level is well above the rim. Surface tension holds the water in, and again gets the better of gravity.

As you have probably guessed, it is this unwillingness of a liquid to increase its surface, that permits mosquitoes, flies, and other insects to walk on the surface of water. The insect is safe from drowning as long as his feet are not wetted by the water, and he is not heavy enough to break through the surface. Even a steel needle will float if it is slightly greased to prevent wetting and is laid very gently and evenly on the surface. If you do not believe that this is possible, try it for yourself. But you will need patience and a steady hand.

When a tube with a fine opening in it is immersed in water, the liquid rises in the tube in apparent defiance of gravity—the smaller the bore of the tube, the higher the rise. In a glass capillary tube with a bore the size of a hair (say, 0.002 inch in diameter), the water will rise to a height of nearly a foot.

If a liquid wets the walls of a tube, the forces of adhesion between liquid and glass must be greater than the cohesion between liquid



Capillarity. (*A*) and (*B*): water rises in glass tubes of small bore; the smaller the bore, the higher the rise. (C) Mercury does not wet glass and is therefore depressed.

molecules. Consequently, liquid molecules crawl rapidly up the sides of the tube, and the liquid column comes on up, too, to keep the exposed liquid surface small. The exposed surface is curved downward, and would be smaller if it were flat across the tube. The rise continues until the upward pull of the surface, trying to contract, just balances the downward pull of the liquid column underneath it.

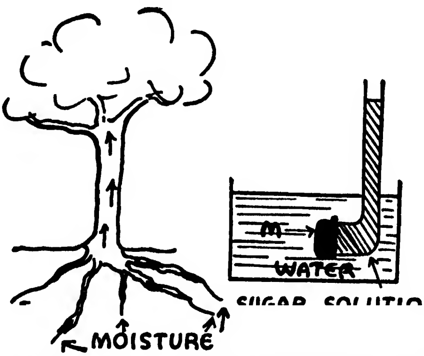
Where tiny crevices or passageways are present in porous materials, capillary action explains many common processes of wetting and the rise of liquids: hence, the rise of oil in lamp wicks, the absorption of ink by blotting paper, the effective drying action of towels, and the rise of moisture in dry soil.

III. *What Is Osmosis and What Does It Do?*

Attempts have been made to explain the upward flow of sap in trees and plants exclusively on a basis of capillarity. Undoubtedly capillarity is involved. But by itself, it is insufficient. The size of the capillary openings would need to be vanishingly small in order for water to rise in them to the top of a tree several hundred feet high.

The problem of the rise and flow of sap in plants has not been completely solved. Besides capillary action, the phenomenon of *osmosis* plays an important role. Osmosis is the process of transmission of fluids through semi-porous partitions. Suppose, for example, that a cube of sugar is tied securely into a small bag made of a special kind of Cellophane that is semi-permeable to liquids. If the bag containing the sugar is immersed in a pan of water, the liquid will penetrate through the Cellophane; and, after a time, sufficient osmotic pressure will be created inside to burst the bag.

The explanation of this behavior is easy enough. Water molecules diffuse into the bag readily through the tiny openings. Sugar molecules, themselves too large to get out, partially block the outward diffusion of the water. Consequently, more water molecules enter than leave the bag, diluting the sugar solution more and more until sufficient pressure is built up to equalize the flow—or until the membrane bursts.



Osmosis. Water penetrates the permeable membrane *M* and dilutes the sugar solution. Osmosis is also partly responsible for the rise of sap in trees.

The roots of plants and trees contain similar semipermeable membranes through which water in the wet earth can diffuse into the sugary sap. Once inside, the water is forced higher and higher until it reaches the leaves, and there evaporates. It is believed that osmotic pressure, with the aid of capillary action, is able to raise the sap to the necessary height.

Osmosis plays a part in many other common phenomena. Like the Cellophane bag containing sugar, dried fruits swell when they are soaked in water. As farmers well know, prolonged rain ruins a crop of ripe cherries: the cherries swell up and burst because water dif-

fuses to the interior of the fruit by osmosis through the skin. Similarly, due to diffusion outward, berries become watery when they are left soaking in sugar.

Osmosis is very important in bodily processes. Liquids and food are usually supplied to living cells by osmosis. Nourishment enters the blood stream in our bodies by a type of osmosis (called *dialysis* in this case) through the walls of the intestines. One of the most vital of the bodily processes involves osmosis of gases rather than liquids: our blood is purified by osmosis of oxygen inward and carbon dioxide outward through the membranes of our lungs.

IV. *What Is Fluid Pressure?*

In the last few pages, we have had occasion to use the term *pressure* a number of times without defining its exact meaning. Commonly, the terms pressure and force are used interchangeably. But in science the word *pressure* has a more limited and precise meaning: pressure is defined as the *force per unit area.* For example, when you ask the service station attendant to inflate your automobile tires to 30 pounds, you do not mean that each tire should contain a weight of 30 pounds of air; nor do you means a total *force* of 30 pounds. What you do mean is a pressure of 30 pounds per square inch, above the pressure of the atmosphere. The actual weight of air contained at this pressure in a $6'' \times 16''$ tire is less than half an ounce; but the total force pushing outward, tending to burst the tire, is nearly 20 tons. This force is calculated simply by multiplying the pressure by the total surface area of the tire:

$$\textit{Force} = \textit{Pressure} \times \textit{Area}$$

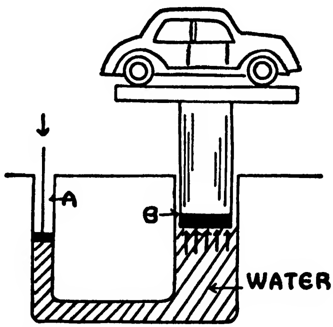
This relation is valid for any fluid—either gas or liquid—no matter what the cause of the pressure.

Furthermore, the pressure acts equally in all directions; it acts always at right angles to whatever surface it is pushing against; and any increase in pressure in a vessel is transmitted equally to all surfaces. These facts constitute *Pascal's Principle.* You recall that we met this principle once before in connection with the force on a sail: the wind always pushes at right angles to the sail, no matter how the sail is oriented relative to the direction of the wind.

One of the most important applications of Pascal's Principle is in hydraulic devices of all kinds. If two pistons of unequal area are connected by a fluid such as water or oil, a small force pushing on

the small piston produces a large force on the large piston. According to Pascal's Principle, the pressures are everywhere equal. Therefore, a push of one pound on a piston of area one square inch, results in a force of 100 pounds on a piston of area 100 square inches. Tremendous mechanical advantage may be attained by hydraulic devices. Hydraulic presses, requiring only moderate fluid pressures, supply forces of many thousands of tons in steel mills and elsewhere. But, as is always the case in such machines, speed is sacrificed for a gain in force.

Hydraulic elevators were very common at one time, but have been replaced almost entirely by the speedier electric elevators. Nowadays, the most common hydraulic devices are automobile hydraulic brakes, and the lifts employed at service stations for elevating automobiles to make greasing or repairing more convenient. In these hydraulic lifts, the large central cylinder is pushed up by water pressure on a piston below ground. If a water pressure of 40



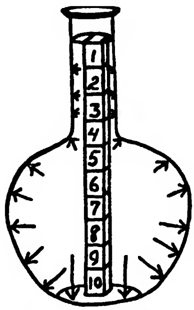
Principle of the hydraulic lift. A small force on the small piston *A* results in a large force on the large piston *B*. The small piston may be replaced by any source of water under pressure.

pounds per square inch is available, then a piston one foot in diameter (area, 113 square inches) will lift a car weighing 113×40, or 4520 pounds.

Pressure in any fluid is due to one of two causes: either compression by some sort of mechanical pumping device; or the weight (head) of the fluid itself. Thus your automobile tires are inflated with air compressed by a pump operated either by hand or by motor. Water pressure in your city mains is probably maintained by pumps; though the system may be of the gravity type, with a reservoir

located high above the level of the city. The pressure on the bottom of the ocean is due entirely to the weight of water above—plus atmospheric pressure.

The pressure due to the weight of a liquid may be calculated readily for any depth. Suppose that we wish to find the pressure, in pounds per square inch, at the bottom of a tank of water 10 feet (120 inches) deep. Consider a column of water of cross section area one square inch and of height 120 inches. The volume contained in this column is 120 cubic inches. Each cubic inch of water weighs about 0.036 pound. Hence, the total weight of the column is 120 × 0.036, or 4.3 pounds. This is the force with which the one-



Pressure in a liquid. Add up the weight of the 10 cubic inches of liquid and you have the pressure on the bottom of the flask (in pounds per square inch). The pressure is transmitted equally in all directions (Pascal's Principle).

square-inch column pushes down on the bottom of the tank, and is therefore the pressure in pounds per square inch.

We heard, in the recent war, of submarines that can submerge to 600 feet below the surface of the ocean. The pressure on a submarine hull at this depth is more than 250 pounds per square inch, and the submarine must be carefully designed to avoid being crushed in. The usual limit for submarines is only about half so deep—not so far down as a diver can go if he breathes a mixture of helium and oxygen. William Beebe, in 1934, went down to 3,000 feet in his bathysphere, a thick-walled steel ball.

As you can see, the pressure in a stationary body of water depends only on the depth and on nothing else. This fact is of special significance. It means, for instance, that the size of the lake stored up behind a dam has nothing to do with the force tending to burst the dam. The pressure, and hence the total force, depends only on

the depth of the water. If Boulder Dam were built right in front of a cliff in such a way that Lake Mead backed up only a few feet behind the dam instead of more than 100 miles, the bursting force would be the same—provided the depth were the same in both cases.

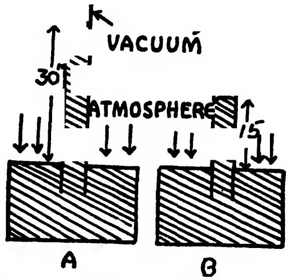
V. *How Does a Barometer Work?*

When we said that the pressure at the bottom of a 10-foot tank of water is 4.3 pounds per square inch, we should have noted that this is the pressure over and above atmospheric pressure. We live at the bottom of an ocean of air from which we cannot escape. Atmospheric pressure, nearly 15 pounds per square inch, is always with us.

The total force resulting from the pressure of the atmosphere inward on our bodies is many tons. You might wonder why we do not feel just a bit crushed. But this pressure is balanced by an equal and opposite pressure inside our bodies. For the same reason, deep-sea fish escape being crushed by the water, even though they live a mile under the surface where the pressure is more than a ton per square inch. It is said that such fish may blow up and burst if they are brought to the surface too quickly. When we go up in an aeroplane or an elevator, or travel rapidly up a mountain where the pressure is reduced, we ourselves are aware of a mild sample of this bursting sensation. Our ears seem to close up; then they "pop" as the excess pressure on the eardrums is released. Aviators know that repeated swallowing helps to equalize the pressure inside and outside the body when one is rising or falling rapidly.

Since most gauges measure pressure above atmospheric, and we ourselves are normally unconscious of air pressure, how do we know that the atmosphere really does exert a pressure of 15 (more precisely, 14.7) pounds to the square inch? A barometer solves the problem. The most accurate form is the mercury barometer, which may be constructed in the following fashion: A glass tube, about 3 feet in length and sealed at one end, is filled to overflowing with mercury. Keeping the open end sealed with the finger, the tube is inverted, and the open end immersed to a depth of an inch or two in a vessel containing mercury. When the finger is removed, the mercury will not all run out of the inverted tube, but the level of the mercury will remain about 30 inches (76 centimeters) above the level in the open vessel. There is a vacuum above the mercury in the closed end of the tube; and the mercury column is supported by

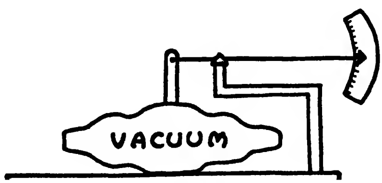
atmospheric pressure pushing down on the mercury outside. In other words, a column of mercury 30 inches high produces a pressure of nearly 15 pounds per square inch at its base, just balancing the atmospheric pressure.



The mercury barometer. (*A*) A column of mercury 30 inches (76 centimeters) high is supported by normal atmospheric pressure at sea level. (*B*) At an altitude of 3½ miles the pressure is only half as great.

The height of the mercury column in the barometer tube will vary as the pressure of the atmosphere varies. Thus, the barometer reading falls as we ascend above sea level. On top of a mountain a mile high, the pressure of the atmosphere is only about 12 pounds per square inch, and the height of the mercury column in the barometer is about 26 inches.

Since the air pressure varies with altitude, barometers serve as altimeters to measure the height above sea level. But a tube containing a mercury column 30 inches high is not a convenient instrument



Principle of the aneroid barometer. The motion of the flexible metal walls of the evacuated chamber is transmitted to a pointer as the pressure varies.

to carry around, and for approximate measurements the mercury barometer is usually replaced by one of the *aneroid* type. This is simply a flat, evacuated pill box with thin flexible metal walls. Through a system of levers, the motion of the walls is greatly amplified and is transmitted to a pointer. As the pressure changes, the

walls of the box move in and out, and the pointer moves over a scale that reads either in inches or centimeters by comparison with the mercury barometer. If the instrument is to be used as an altimeter, the scale may read directly in feet elevation. Aeroplanes are equipped with aneroid barometers of this type.

The barometer is not entirely satisfactory as an altimeter, because the pressure of the atmosphere changes continually, even at sea level. For reasons that we shall discuss in Chapter Ten, these changes in air pressure frequently presage a change in the weather. Hence, the very feature that makes a barometer unreliable as an altimeter makes it valuable in forecasting the weather. As you undoubtedly know, a falling barometer often indicates an approaching storm; a rising barometer, clear weather. Incidentally, all true barometers measure atmospheric pressure and nothing else. Many devices commonly sold as barometers measure only temperature, humidity, or some other factor that is not reliable in predicting weather changes.

VI. *How Does a Siphon Work?*

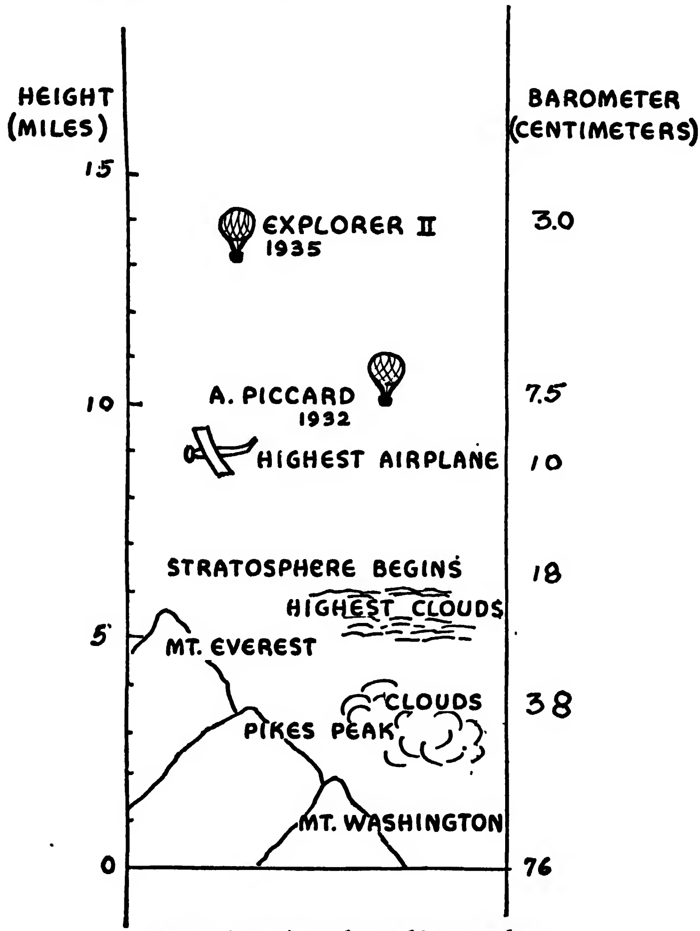
Very often we do not realize that air has weight, any more than we are conscious of atmospheric pressure. But air is made up of a mixture of oxygen (21 per cent), nitrogen (77 per cent), and other gases (water vapor, carbon dioxide, argon, etc., 2 per cent), that have mass, and are therefore attracted to the earth by gravity. A cubic foot of air weighs a little more than an ounce. A small room, $10 \times 10 \times 10$ feet, contains 75 pounds of air.

It is the weight of the air that causes atmospheric pressure—just as it is the weight of the water that causes pressure at the bottom of the ocean. We can calculate that the atmosphere would extend to a height of about 5 miles above the surface of the earth, if the density remained the same as at sea level all the way to the top. In reality, as we ascend above the surface, the density of the air decreases rapidly at first; then gradually tails off to nothing at a height of some hundreds of miles.

No definite limit can be set to the depth of our atmospheric ocean. We do know, however, that half of all the air lies below an altitude of 3½ miles. At 72,000 feet (nearly 14 miles), the highest point ever reached by man,* the pressure and density are only 1/25

* This altitude was attained by Captains A. W. Stevens and O. A. Anderson of the United States Army Air Corps during the flight of the stratosphere balloon,

as great as at sea level. This means that 96 per cent of all the atmosphere lies below the height of 14 miles. But the aurora borealis,



A few facts about the earth's atmosphere.

and other phenomena, indicate that there is still a little air at a height of at least 600 miles.

People used to say—and perhaps some still do—that nature abhors a vacuum. This is, of course, untrue. By far the greater

Explorer II, which took off from a point near Rapid City, South Dakota, on November 11, 1935. The flight was sponsored jointly by the National Geographic Society and the U. S. Army Air Corps.

portion of the universe is almost a perfect vacuum. Here on earth, we gain the impression that a vacuum is an unnatural state of affairs, because atmospheric pressure is always with us. But even here, as Galileo is supposed to have said, "nature evidently does not abhor a vacuum above a column of mercury 30 inches high." Mercury is a very heavy liquid. It is 13.6 times as dense as water and more than 10,000 times as dense as air. That is the reason why the atmospheric pressure of 14.7 pounds per square inch supports a column only 30 inches high. But what about water? How high would a column of water need to be before nature no longer abhorred a vacuum? Evidently, 13.6×30 inches, or about 34 feet.

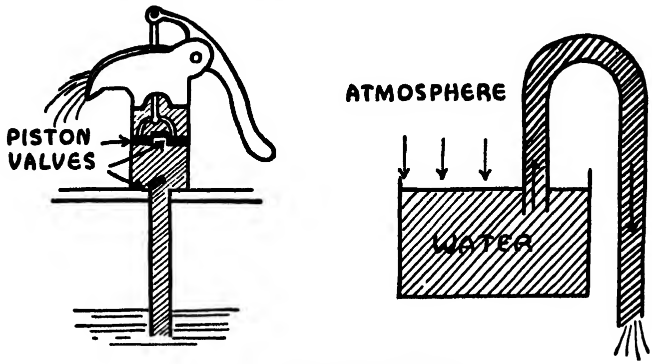
This distance, 34 feet, is of very practical importance to any one who is planning to pump water from a well with the aid of a suction pump, or who wishes to siphon water over an obstacle. A suction pump does not really suck water up a pipe. Air pressure on the outside pushes the water up when the pump creates a partial vacuum inside the pipe. The air pressure cannot force the water up farther than 34 feet, because at that height, the weight of the column of water just balances the weight of the atmosphere. In actual practice, a lift of about 28 feet is considered good performance for a suction pump at sea level, because the pump cannot create a perfect vacuum. So if you dig a well and find that the water level is deeper than 28 feet, you should plan to install a force pump instead of a suction pump.

Similarly, it is useless to try to siphon water over a hill more than 34 feet high. The siphon, too, depends for its action on the pressure of the atmosphere. As you no doubt know, the siphon is a self-operating device which first lifts a liquid and then deposits it at a level lower than the starting point. This last qualification, "lower than the starting point," is important. In contradiction to the Principle of the Conservation of Energy, we should be getting something for nothing if a siphon would lift water from a lower to a higher level. You cannot siphon water out of a well or out of the bottom of a leaky boat.

It is interesting to study in detail the action of a siphon. Consider an inverted U-shaped tube with one end immersed in a vessel of water, and the other end, open to the air, hanging over the side of the vessel. Once the tube is initially filled with water by suction or other means, water will continue to flow out of the vessel until one of two things happens: either the water level in the vessel falls below

the immersed end of the tube; or the level of the water outside rises to the level of the water inside. The question is: just why does this flow take place?

Suppose we imagine the water in the inverted U-tube to be replaced by a snug-fitting, nearly-frictionless cable, of just the length of the tube. The longer end of the cable on the outside of the vessel would outweigh the shorter end; and, as a result, the cable would slide through the tube, with the long end pulling the short end behind. Now, our cable analogy is bad in one respect: the cohesive



The lift pump and the siphon.

forces in water are small, and the long column of water cannot actually pull the short column along after it. But suppose that the cable were cut just at the top of the bend in the U-tube. Then, as the long end of the cable began to fall out of the tube, a vacuum would be formed between the cut ends. Air pressure would push the short end along after the long end, just as though the cable were still uncut. In exactly the same way, air pressure on the surface of the water in the vessel pushes water up the tube when the long column falls out the open end. The greater the difference in height between the open end of the tube and the water level in the vessel, the greater is the net pressure—hence, the greater the speed of flow.

VII. *What Are the Effects of Buoyancy in a Fluid?*

One of the most important results of fluid pressure is the phenomenon of buoyancy. Probably, people have always been aware that a body appears to become lighter in weight when it is immersed in water; but the first practical application of this fact was made by the Greek scientist, Archimedes, somewhere around the year 250 B.C

Incidentally, I think that we may call Archimedes a scientist rather than a philosopher, because he was apparently a very practical sort of person. Unlike Aristotle and most of the other thinkers of his day, Archimedes performed numerous experiments and has several inventions to his credit.

The principle discovered by Archimedes and bearing his name is usually stated as follows: *A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.*

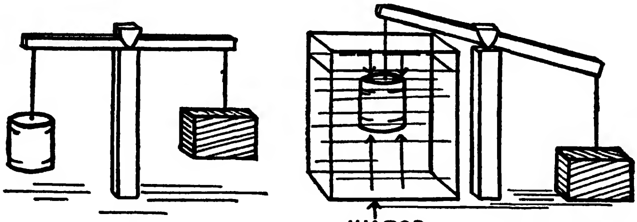
Among other things, Archimedes' Principle is useful for identifying the material contained in an object of irregular shape. For example, suppose that a block of aluminum and a block of lead are of equal *weight* when they are weighed in air. What will happen if they are hung on strings and are weighed while dangling immersed in water? Both will lose weight. But the aluminum, having greater volume than the lead, will be buoyed up more; that is, the aluminum will register the greater loss of weight.

By making the weighings accurately, the volume, and hence the density (mass per unit volume) of any material can be determined; and very often, the material can be identified from its density. This is one of the methods that prospectors use for identifying ores and metals. Also, it is the application made by Archimedes himself when he first discovered the principle of buoyancy. The story of this discovery has been told many times, but perhaps it is worth repeating.

The Emperor Hiero of Syracuse had ordered a new gold crown for himself. For some reason, he suspected that the goldsmith had cheated by mixing silver or other less expensive metal in with the gold. So Hiero called on Archimedes to test the purity of the gold without damaging the crown. At first Archimedes was puzzled as to a method for doing this; but according to the story he solved the problem in a flash when he noted the buoyancy of his own body while bathing. So great was his excitement that he jumped out of the bath and ran naked into the street crying, "Eureka" ("I have found it"). It turned out that when the Emperor's crown was immersed in water, the loss of weight was greater than it should have been for pure gold. Evidently, the crown was adulterated with a lighter (less dense) metal. As a result of Archimedes' tests, the dishonest goldsmith was executed at the order of Emperor Hiero.

Archimedes' Principle can be explained entirely on a basis of pressures. Thus, a boat automatically sinks to such a level that the

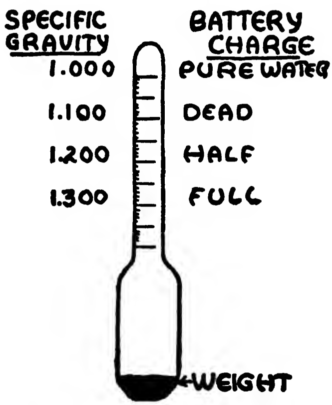
force upward due to pressure on the bottom just equals the total weight of boat and contents. If an object is completely immersed,



Archimedes' Principle. An object immersed in a fluid is buoyed up due to the excess pressure on the bottom.

the buoyant force can be accounted for by the difference between the pressure pushing upward on the bottom and the smaller pressure pushing down on the top. In accordance with Archimedes' Principle, this buoyant force is exactly equal to the weight of fluid displaced.

The level to which a floating object sinks into a liquid obviously depends on the relative densities (or specific gravities) of the liquid and object. Thus, a hydrometer measures the charge in your auto-



A floating object displaces a quantity of liquid equal to its own weight. The hydrometer sinks deeper as the acid is used up and the specific gravity becomes less.

mobile battery, because the weighted bulb sinks lower as the heavy acid is used up and a greater proportion of the less dense water is left behind.

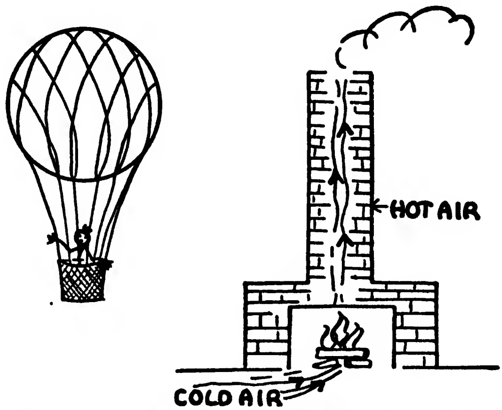
If an object is dense enough to sink beneath the surface, almost certainly it will go clear to the bottom. Tales of sunken ships floating a few feet under the surface of the ocean may be pure fiction. There is only one way that such a thing could happen: If a waterlogged boat were just a shade more dense than the surface water, then water some distance under the surface might be sufficiently compressed, or sufficiently different in salt content or in temperature, so that its density would be greater than the density of the boat. Normally, however, an object will float with part (perhaps a very small part) projecting above the surface, or it will sink to the bottom.

This question of buoyancy is, of course, very important in the operation of a submarine. A submarine submerges by taking aboard just enough water to make its total weight almost exactly equal to the weight of the water it displaces, and maintains itself at a certain level by the action of rudders. When it wishes to come to the surface again, part of the ballast water is forced out by means of compressed air. The density of sea water is a little greater than the density of fresh water, so a submarine has to be especially careful when operating around the mouth of a river.

Archimedes' Principle applies to gases as well as to liquids. A pound of feathers, weighed in the air, would weigh about 1.01 pounds in a vacuum. In air, the feathers are buoyed up; that is, suffer an apparent loss of weight, by an amount equal to the weight of air displaced. While the errors that it causes in weighing are usually very small, air buoyancy is of practical importance in many cases. Thus a balloon rises because the density of the light gas inside is less than the density of the air outside. A balloon stops rising as soon as the air becomes so thin that the displaced air weighs the same as the balloon and its contents. Since the gas (hydrogen or helium) used to inflate the balloon has weight, the ideal balloon would be a very light-weight bag, completely evacuated. Of course, an evacuated balloon would be impossible, because the walls would collapse under air pressure. So the next best thing is a light bag inflated to atmospheric pressure with a light gas.

Pumping the gas in the balloon up to a high pressure would only reduce the lifting power, because the overall weight of the balloon would be increased. This is an important point, since people often think that if they could only put enough hydrogen into the tires of their automobile, the car would float away. Or they think that a tank of compressed helium weighs less than an empty tank. But

Archimedes' Principle tells us that the exact reverse must be true: the higher the pressure, the greater the weight of the contents, and the less the net lifting power.



Archimedes' Principle applied to gases. A balloon and a chimney.

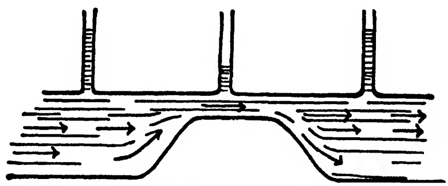
Since hot air is less dense than cool air, Archimedes' Principle tells us that hot air will rise, just as will a hydrogen-filled balloon. In fact, many years ago before hydrogen was readily available, hot-air balloons were rather common. It is the rising of hot-air currents that causes the shimmery appearance above a stove or hot pavement —we shall see more about this shimmery appearance later. Similar convection currents cause a chimney to draw. The hot air in the chimney rises like a balloon, and cold air rushes in behind, through and around the fire. The taller the chimney, the greater is the difference in atmospheric pressure between top and bottom—hence, the better the draft.

VIII. *What Happens When Fluids Flow?*

As a matter of fact, the buoyancy of hot gases does not explain completely the behavior of chimneys. When there is no wind, Archimedes' Principle accounts for the draft. But when the wind is sweeping across the top of the chimney, the pressure is reduced by this motion of the air; and the draft is thereby improved. In exactly the same way, a stream of air blowing across the end of a tube in a perfume atomizer or spray gun reduces the pressure and pulls liquid up the tube (actually, of course, atmospheric pressure pushes it up), and into the air jet, where a spray is formed. Here is some-

thing new about pressures! The pressure seems to be lower inside a blast of air than outside where the air is stationary.

Strictly speaking, everything that we have said about pressure in a fluid applies only when the fluid is at rest. *Whenever a gas or a liquid is flowing, the pressure within the stream is lower than the pressure outside; and the greater the velocity of flow, the less the pressure.* This somewhat surprising fact is known as *Bernoulli's Principle,* and it can be proved theoretically by mathematical deduction,* or can be demonstrated experimentally in a number of different ways. That it applies to a liquid like water, as well as to gases, may be shown by attaching pressure gauges to a horizontal water pipe in which there is a constriction. Water flows at a higher speed through the constricted area than through the large portion of the



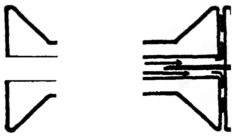
Bernoulli's Principle. Where the velocity of the water is greatest (in the constricted area of the pipe) the pressure is least.

pipe. One would naturally think, offhand, that squeezing the water into this small space would result in an increased pressure. But in accordance with Bernoulli's Principle, the gauges show that just the reverse is true: Where the water is flowing most swiftly, the pressure is the lowest.

You can demonstrate Bernoulli's Principle for yourself in a rather spectacular fashion, with the aid of an ordinary spool, a common pin, and a piece of cardboard about an inch square. Stick the pin through the center of the cardboard, and insert the pointed end of the pin into the hole of the spool. The cardboard then lies flat across the end of the spool and is prevented from slipping sideways by the pin. Now, holding the card in place momentarily, blow steadily on the other end of the spool. Instead of blowing the card

* A very brief explanation is the following: When the speed of the fluid is increased (that is, when the fluid is accelerated), Newton's Second Law of Motion tells us that a force must be provided; this force can be supplied only by the pressure in the fluid itself; and the pressure outside the stream must therefore be greater than the pressure inside.

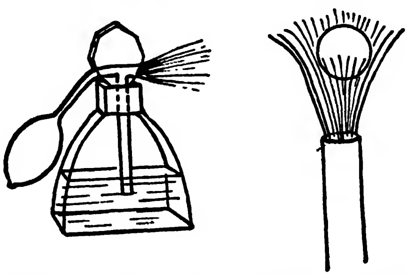
away, the blast of air only makes the card stick to the spool; and, paradoxically, the harder you blow, the closer the card sticks. Pressure in the air current between spool and card is reduced in accordance with Bernoulli's Principle. Atmospheric pressure on the other side of the card then pushes the card up tightly against the spool.



The card cannot be blown away from the spool!

Bernoulli's Principle warns us that fast-moving vehicles and ships should not pass or move side by side too close to each other, lest the reduced pressure in between cause them to collide. Thus, when ships pass in a narrow canal, one ship is always tied up securely while the other is going by. Likewise, it is dangerous for a person to stand too close to a speeding train. The flow of air reduces the pressure between his body and the train; and atmospheric pressure on the outside may push him against the moving cars.

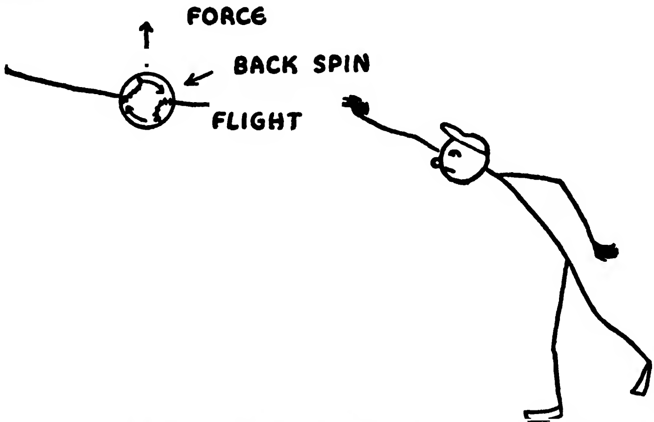
Besides aspirators, atomizers, and spray guns, there are other practical applications of Bernoulli's Principle. One of these is the carburetor on your automobile. Air, sucked into a cylinder on the downstroke of the piston, passes over a tube or jet, the lower end of



Applications of Bernoulli's Principle. (*A*) Atomizer. (*B*) Celluloid ball balanced on a jet of water or air.

which is immersed in gasoline. Just as in the atomizer, the pressure is reduced in the air blast, and gasoline is pushed up the tube, into the blast, by the excess pressure of the relatively stationary surrounding air. The volatile liquid soon vaporizes and mixes with the air to form an explosive mixture.

In shooting galleries, it is common to see light celluloid balls balanced on jets of water. Perhaps you have wondered why the balls do not fall off—before someone shoots them off. Again, Bernoulli's Principle supplies the answer, or at least most of the answer. The fluid velocity being large in the center of the jet, the pressure is small; and when the ball starts to fall to one side, it is pushed back into the stream by the excess pressure of the still atmosphere. In the case of a ball supported on a water jet, adhesion between ball and liquid also plays a role. But a ball may be balanced just as readily on a jet of air, where Bernoulli's Principle supplies the complete explanation.



The curving of a baseball. Backspin causes the ball to curve upward in its flight.

Do you know how a pitched baseball is made to follow a curved path? If you are either a player or a fan, you are, of course, aware that a curve-ball is always a rotating ball. The pitcher puts the spin on the ball when he throws it. Bernoulli's Principle then tells us why and how the ball is going to curve in its flight. Let us suppose, for example, that a pitcher wishes to throw an upcurve, or as it is sometimes called, an upshoot. He then puts back-spin on the ball; that is, he sets the ball to rotating about a horizontal axis, with the top of the ball moving back toward himself. The ball tends to drag a layer of air around with it as it rotates. As a result, the velocity of the air streaming past the ball is greater at the top of the ball than at the bottom. The pressure at the top is thus reduced, and the ball curves upward in defiance of gravity, or at least does not drop so rapidly as it would under the influence of gravity alone.

Top-spin on a ball results in a dropcurve. Tennis and ping pong players know that top-spin greatly aids gravity in bringing the ball down inside the baseline after a hard drive over the net. Rotation about a vertical axis is necessary for an outcurve or an incurve. The slice and hook in golf are also caused by just such a spin about a vertical axis. The ball is set to spinning when the face of the golf club is pulled horizontally across the face of the ball during the stroke.

Since a baseball cannot change its direction or speed of rotation (except to slow down) after it leaves the pitcher's hand, it would seem that a true break in the path of the ball is a physical impossibility. The ball may, however, curve more sharply toward the end of its path, if the forward motion is considerably reduced by air resistance, while the spin is maintained. This increased curvature is what we call a sharp-breaking curve. But no pitcher can make a ball curve first in one direction, then in the opposite direction; nor can he throw a corkscrew curve. So-called "double breaks" are either optical illusions or figments of the imagination.

CHAPTER FIVE

ELECTRICITY: SOME OF ITS MANIFESTATIONS

I. *What Is Electricity?*

Electricity, in its many manifestations, is familiar to all of us, but it remains nevertheless a subject of interest and even of mystery. In order to clear up some of the mystery, let us begin by asking and attempting to answer the question, *What is electricity?*

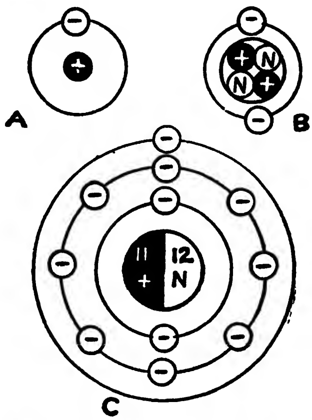
Fifty years ago science did not know the answer. Electricity was vaguely assumed to be some sort of fluid (or perhaps two fluids—positive and negative); and even today it is often referred to as "the juice."

The physicist of 1930 might have considered the question quite simple. He could have answered smugly, and not very informatively, by saying that *everything* is electricity. Getting down to details, he would have told us that all matter is made up of infinitesimal bits called atoms, and that the atoms themselves consist of electric charges and nothing else. Each atom was believed to contain a massive positively-charged core or nucleus, with negative electrons revolving around the nucleus much as the planets revolve around the sun. Atoms of one chemical element differed from atoms of another element only in the number and arrangement of their electrical particles. In any normal atom the number of negative electrons equalled the number of heavy positive protons; and as a result the atom as a whole was neutral and its electrical nature escaped detection. But when some of the planetary electrons were torn away from their parent atoms, electrical phenomena became evident, because electrons then constituted free negative charges, while the atoms were left behind charged positively.

After the early years of the decade 1930–40, the physicist would have modified his story a little. He would not have been so glib about the sun-and-planets idea, because it had been found that this picture did not fit all the experimental facts. A new, complicated mathematical theory of the atom, called the *quantum theory*, was rising to prominence—a theory that spoke about probabilities instead of certainties, and that talked more about the wave nature than about

the particle nature of electrons and atoms. All this was most disturbing, because we could no longer obtain a definite mental picture of an atom. Indeed, we were forced to visualize a peculiar smeary sort of atom in which it was never certain just what the electrons were doing or where they were located. But nature is seldom as simple as we should wish, and the new theory has had great success in explaining and predicting experimental facts. No more than that can be asked of any theory.

The physicist might, furthermore, have been disturbed about the *neutron*, a surprising atomic particle discovered in 1932 by Chad-



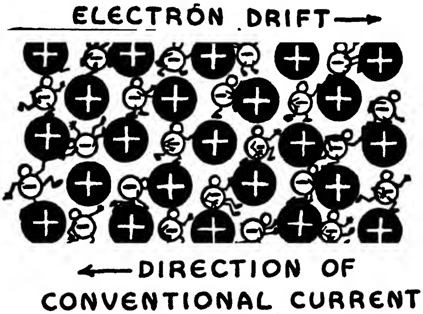
A rather naïve picture of some atoms. (*A*) *Hydrogen*, with one proton in the nucleus and one extra-nuclear electron. (*B*) *Helium*, with two protons and two neutrons in the nucleus; two extra-nuclear electrons. (*C*) *Sodium*, with 11 protons and 12 neutrons in the nucleus; 11 extra-nuclear electrons distributed in three "shells."

wick in England. This new particle, which is only observed when atoms are blasted to pieces by very high-speed atomic bullets, has a mass nearly that of the proton, but has no electrical charge. Nowadays it is believed that all atomic nuclei except hydrogen contain neutrons as fundamental building blocks. Hence we can no longer hold, without qualification, that all matter is made up exclusively of electrically charged particles.*

* Protons and neutrons are approximately equal in mass, and are about 1,800 times as heavy as electrons. Several additional sorts of particles having transitory existence have been discovered during the past few years: (1) *mesotrons* (heavy electrons)—of mass about 200 times that of ordinary electrons and observed in studies of cosmic rays; (2) *positrons* (positive electrons)—short-lived particles

But with all these new concepts, the extra-nuclear or planetary electrons remain much as before; except that we think of them as being located in vaguely defined regions surrounding the nucleus, rather than in definite orbits. In fact, in the case of solid materials, many of the electrons are free to move, not being tied down to any particular atom. In metallic solids, these free electrons can be urged to travel preferentially in one direction, and then we have an electric current.

And so, if we mean by the term electricity simply an electric current, the answer to our question is easy. An electric current is



Current flowing in a wire: showing free electrons drifting through the maze of stationary metal atoms.

nothing more nor less than a swarm of electrical charges in motion. These charges, in the case of a wire or other solid body, are free electrons: but if the positively charged metal atoms (which are surrounded by the swarm of free electrons) were not rather firmly fixed in their places, the charged atoms themselves would tend to move in the opposite direction. Such atomic motion actually occurs when currents pass through liquids and gases. There, the positively charged atoms and molecules (called *ions*) are not held in place by one another, and their motion constitutes a part of the current. In this connection it is interesting to note that the conventional direction of electric current is from positive to negative; that is, the direction in which positive charges would move. This convention was

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resulting from certain transmutation experiments and also appearing in cosmic rays; (3) *neutrinos*—tiny uncharged particles for which there is some experimental evidence though they have not yet been definitely isolated and established experimentally.

adopted before the discovery that in most cases it is the negative electricity that actually flows.

More precisely, the term electricity refers not to the electric current but to the actual electric charges (electrons and ions) whose motion constitutes the current. If we accept this meaning, we cannot say to this day what electricity is. An electron, we know, is an electric charge. But what is an electric charge? Something that attracts unlike charges, and repels like charges, and manifests itself in various other ways when it is in motion. But we still have no mental picture of what an electron really looks like. You can speculate about the appearance of an electron as well as I can, and as profitably. I am able to tell you what an electron *does,* how it *behaves,* but *not* what it actually *is.* We mortals are limited by the information that we receive through our senses. As we shall see again and again, such matters as the true, fundamental nature of electrons, atoms, and light waves lie outside the realm of our everyday experience; and a satisfactory description always eludes us.

II. *What Is an Ampere?*

When electric currents began to be studied quantitatively, it was necessary to decide upon a unit of current. The *ampere* is now the accepted unit, defined by international agreement. This unit of electric current is related to the fundamental units of length, mass, and time, but the relation need not concern us here. We do need to have some idea how much current an ampere is, and for this some examples will be useful.

A 100-watt electric lamp bulb on your 110-volt house circuit takes nearly one ampere; a 60-watt lamp takes a little more than half an ampere. An electric toaster or an electric iron requires several amperes—perhaps 4 or 5. On a cold morning your automobile self-starter draws several hundred amperes from the battery. What does all this mean in terms of the flow of electrons? Simply this: when a wire carries a current of one ampere, the incomprehensibly large number of 6×10^{18} electrons* flow past any point in the circuit each second.

* The symbol 6×10^{18} ("six times ten to the eighteenth power") is shorthand notation for 6 with 18 zeros after it; that is, six billion billion. It is quite hopeless to visualize such a large number. If you wish, think of a cube of sand a quarter of a mile on a side. The number of grains of rather coarse beach-sand contained in this sizable mountain might approximate 6×10^{18}.

But you should not think that this swarm of electrons darts along at express-train speed. If we assume one free electron for each metal atom, then, in an ordinary lamp-cord wire carrying one ampere, the electrons drift through the wire at the surprisingly slow rate of one foot per hour. It is true that when this same current is in a tiny wire such as the filament of a 100-watt lamp, the electrons (being fewer in number) move a bit faster. But even here, where the electrons are smashing and pounding their way through the maze of metal atoms at such a rate that the atoms are set into violent agitation and the wire becomes very hot—even here, the electrons are drifting along at the leisurely rate of one foot in ten seconds.

Incidentally, if we were obliged to buy free electrons by the pound, they would be very expensive indeed. Each electron weighs 9×10^{-28} gram,* and simple arithmetic enables us to calculate that at the average cost of electrical power (about three cents per kilowatt hour), we pay $80,000 for moving each pound of electrons through our house circuit. But fortunately, electrons are relatively efficient as carriers of energy: on the 110-volt circuit, one ounce of electrons flowing through a 100-watt lamp will operate it continuously for 200 years.

III. *What Determines the Flow of Current?*

Since the electrons flow at slow speed through a wire, you might wonder why the swarms of electrons everywhere in the circuit begin to move simultaneously at practically the instant you close the switch. This must be so, since the current flow is equal at all points in a closed circuit. And what determines how much current shall flow in any given circuit?

The current begins to flow everywhere simultaneously because, back at the source of power, an excess of electrons is piled up; and since electric charges of like sign repel each other, some of the electrons are pushed off down the wire. Thus the electrons, by their mutual repulsions, force their neighbors to move along. The wave of repulsion travels down the wire at nearly the speed of light, 186,000 miles per second—so fast that for all practical purposes the current appears to start instantly. In just this same way, when water starts

* The symbol 9×10^{-28} ("nine times ten to the minus twenty-eighth power") is shorthand notation for 9 divided by 10^{28}, or 0.0000000000000000000000000009. About 3×10^{28} electrons weigh one ounce. If the earth were made of water, it would contain as many drops as there are electrons in one ounce.

to flow into one end of a filled pipe, water starts to flow out the other end very soon thereafter.

If the excess supply of electrons at the source of power that starts the current is not replenished continuously, there is only a momentary surge of current, as in the case of a stroke of lightning or a static spark. But a battery or generator steadily maintains a state of excess charge at its terminals; hence a current flows continuously if the circuit is closed.

Now this piling up of charge results in what we call an electrical pressure difference or *potential difference,* a quantity whose convenient practical unit is called the volt. By analogy with the flow of water through a pipe, the voltage is often compared to the head or pressure. A large voltage forces a large current through a given piece of wire, just as a high pressure forces a big stream of water through a given pipe.

Furthermore, any wire offers resistance to the flow of electric current, just as a pipe offers resistance to the flow of water. For a given voltage, the greater the resistance the less the current. The electrical resistance is measured in units called ohms. A very simple and famous expression, known as *Ohm's Law,* gives the relation between amperes, volts and ohms as follows:

$$\textit{Current in Amperes} = \frac{\textit{Potential in Volts}}{\textit{Resistance in Ohms}}$$

For example, if your electric toaster has a resistance of 20 ohms, it will take a current of 110/20, or 5.5, amperes on the 110-volt circuit. If you tried to use this same toaster on a 6-volt storage battery (such as you have in your automobile) the current would be only 6/20, or 0.3, ampere—far too little to heat the toaster appreciably. Hence electrical appliances must be used on approximately the voltage for which they are designed.

To sum up: the current in a circuit normally depends on the voltage of the generator and on the resistance to the flow of electrons offered by the wire. Once the voltage is determined by the generating plant, the current can be varied only by increasing or decreasing the resistance contained in the circuit. As we shall see later, there are some apparent exceptions to this rule, but only when unsuspected sources of voltage are located within the circuit.

IV. *What Is the Difference between a Conductor and an Insulator?*

From what we have said about the conduction of electricity, you are probably ready to agree that the resistance of a piece of wire

should depend on the size and shape of the wire. This is indeed so. A long wire offers greater resistance to the flow of electrons than does a short wire. A large, fat wire contains more free electrons than does a small, thin wire of the same length. Hence the large wire has less resistance to current flow.

But the resistance depends also on the nature of the material in the wire. The resistance is small provided a substance contains an abundance of freely mobile electrons, and the electrons are only slightly hindered in their motion as they drift through the maze of stationary atoms. All substances conduct electricity a little—even materials like porcelain, rubber, glass, and sulfur, which we call insulators. But the insulators contain so few electrons that can be moved along by a voltage difference that, in practice, they allow only a negligible current to flow.

Metals are by far the best conductors of electricity. In fact, one of the chief characteristics that distinguishes a metal from a non-metal is its high electrical conductivity. But even metals vary among themselves considerably. The resistance of a metal usually increases as the temperature is raised. Copper, the best conductor among the less expensive metals, is almost universally used for transmission of electricity. Silver and gold are excellent conductors. Aluminum is better than copper, weight for weight, but it costs a little too much to be used extensively.

In the transmission of power, we employ the best conductor available in order that as little power as possible may be lost in heating the transmission line. For other purposes, however, the poorer conductors are often used because they happen to have other desirable properties. Thus, tungsten is usually the metal chosen for the filaments of electric lights, because it has a high melting point and evaporates very slowly even when white hot. In heating devices such as stoves, toasters, and electric irons, various high-resistance alloys are commonly employed. These alloys usually contain metals such as nickel and chromium that do not readily corrode when heated in air.

If you insist on going still further into the matter and want to know why a metal possesses a copious supply of freely mobile electrons, while an insulator lacks such a supply, I shall be obliged to answer simply that things are made that way. We do know that the differences lie in the structure of the atoms; and the quantum theory is now able to give a fairly good mathematical explanation of elec-

tronic conductivity. But the question, like so many of a fundamental nature, at present remains unanswered in simple concepts.

V. *What Is Static Electricity, and What Causes a Spark?*

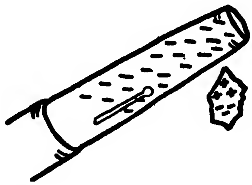
We have said that electrical charges in motion constitute a current. Can we detect charges that are not in motion? Yes, we can, provided there is an excess of either positive or negative charges, for then they exert attractive and repulsive forces that we can observe or measure. Here is a simple experiment to demonstrate: take your fountain pen (or comb, or any object made of rubber or other nonconducting composition) and rub it briskly on your wool coat sleeve; now bring the pen close to a tiny bit of paper not much bigger than a pin-head, and the paper will jump up and attach itself to the pen. Here you have a demonstration of the attractive forces between positive and negative static electric charges. Incidentally, the experiment will work better if you do it on a dry day; otherwise the charges on the pen are likely to escape by conduction along a film of moisture on the surface.

This phenomenon just described was probably the first electrical experiment ever performed by man. It was known to the early Greeks, who electrified amber by friction. Let us see just what happened in our experiment. Rubber, though a nonconductor, has considerable affinity for electrons; while wool gives up some of its electrons rather easily. Consequently, when these two materials were brought into contact, some electrons were removed from the wool and attached to the rubber. This left the wool positively charged and the pen negatively charged. Since the pen is an insulator, the electrons were stuck in one place and were not free to flow off to ground (through the experimenter's body), as they would have done if the pen were made of metal.

Now, paper, though a poor conductor, is by no means a perfect insulator. Consequently, when the negatively charged pen was brought close to the scrap of paper, electrons were repelled to the far end of the scrap, leaving an excess of positive charge at the end of the paper nearest the pen. Hence the attraction between negative pen and positive paper.

You have seen many other examples of static electricity. Often its presence is revealed only when the charge builds up such a high potential that a spark appears; that is, a momentary current flashes through the air and neutralizes the excess charges. Thus, on a dry

day, your hair (or the cat's fur), when brushed, stands on end due to mutual repulsions; and tiny sparks produce a crackling sound as they pass from hair to brush relieving the electrical tension. Doubt-



Negatively charged fountain pen picks up a neutral scrap of paper after charging the paper by induction.

less you have walked across a dry wool rug and have been startled by a spark and a shock when you touched a grounded metal object such as a pipe or radiator. Your shuffling feet removed electrons from the rug until your body was negatively charged to a potential of many thousands of volts. Gasoline trucks drag chains along the road in order that the static charges may pass off harmlessly to the earth without sparking and igniting the highly explosive fumes. Lightning is a gigantic spark between positively and negatively charged clouds or between a charged cloud and the earth.

Static effects are usually characterized by huge potentials or

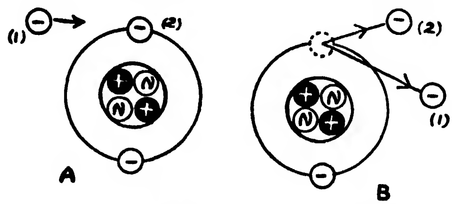
An electrically charged cat.

voltages accompanied either by small currents or by currents of very short duration. A spark is all over in less than one tenth of a second —sometimes in as little as a millionth of a second. But two large spheres, separated by a distance of one centimeter, must be charged to a potential difference of 30,000 volts before the electrical tension

is sufficient to force a spark through the resisting air. If the spheres are a foot apart, the potential difference must be nearly a million volts before a spark will pass. Hundreds of millions of volts are needed to start a lightning flash a mile long!

VI. *How Does an Electric Current Flow through a Gas?*

We have seen that free electric charges are essential for the flow of current. In the case of a metal wire, the charges are free electrons. But the question naturally arises, what are these charges and where do they come from when a spark or other electrical discharge passes through a gas such as air? Air, we know, is normally an insulator; but when the electric strength becomes intense enough, carriers of charge appear suddenly; and there is a surge of current accompanied usually by noise, heat, and light. You might suppose that the current consists simply of electrons jumping out of one charged body and



Ionization of a helium atom by collision. (*A*) Neutral atom about to be struck by a speeding electron. (*B*) After collision: electron knocked out of the atom leaving a positive ion behind.

into the other. But such is not the case. The electrons are attached too firmly to the metal to do that. Instead, free charges (electrons and ions) are formed in the gas itself. These charges serve to transport electricity from one point to another, giving up their own electrical charge on coming in contact with a conducting object.

Here is what happens. A very few free electrons are always present in the air. These electrons have not automatically detached themselves from the neutral gas molecules, but have been blasted loose by cosmic rays or by radiation from stray bits of radioactive material. If now a highly charged object is brought into the neighborhood to attract or repel one of the free electrons in the air, the electron will presently zip along at such a high speed that when it strikes a neutral gas molecule it will knock another electron loose, leaving the molecule behind as a positive ion. Each of the two free electrons (the original one plus the one blasted out of the neutral molecule) immediately repeats this process of ***ionization by collision***, thus forming

two new pairs of electrons and positive ions. And so the process continues, until, in a millionth of a second or less, this geometrical progression results in a tremendous avalanche of free charges which are plentiful enough to carry considerable current through the previously non-conducting gas.

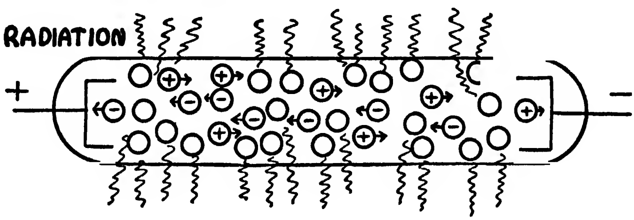
When the gas pressure is reduced, the nature of the spark changes. Suppose that we seal two pieces of metal (called *electrodes*) into the ends of an air-tight container, such as a glass tube, and that we pump out part of the gas contained in the tube, leaving a partial vacuum. If the electrodes are now attached to a source of high voltage, we shall discover that an electric discharge may be initiated much more readily in this partial vacuum than at atmospheric pressure. Lower voltages are required, because the gas molecules are farther apart, and the free electrons are able therefore to pick up more speed between ionizing collisions. Then, too, once a current has started, the positive ions aid the process by swarming together and building up intense local forces.

Warplanes, flying in the rarefied upper atmosphere, would have serious trouble with electric discharges in the high-voltage ignition system if they tried to use the same designs that are successful in automobiles and other land vehicles. Two remedies for this trouble are available: either the exposed metal parts that are very different in voltage must be kept far away from one another; or else the ignition system must be sealed up airtight and kept at normal atmospheric pressure.

If the pressure of the gas is reduced to less than one one-hundredth of atmospheric pressure (that it, more than 99 per cent of the gas is pumped out), the discharge changes its character completely. The localized, noisy sparks spread out into a velvety, silent glow that fills the whole tube with colored light characteristic of the gas. The bright red neon advertising signs, so common these days, are simply long thin glass tubes, bent into the form of letters or other desired shapes. The tubes contain neon gas at about a hundredth of an atmosphere pressure; and electric glow discharges of the sort just described are maintained in the neon by transformers that give 10,000 volts, but only a few hundredths of an ampere current. The process of light emission from such glowing gases is a matter that we shall discuss further in Chaper Seven.

There are other kinds of discharge that somewhat resemble static sparks in appearance, but require lower voltages. One example is the carbon arc, employed extensively at one time in street lighting,

but now largely abandoned. Because they are the brightest of all lights, such arcs are still used in high-power searchlights, and they serve also as sources of ultra-violet light in one type of sun-lamp. The discharge is initiated by touching the electrodes together, then drawing them apart. Once started, the arc of nearly a centimeter in length may be maintained with a hundred volts or less. By comparison, a one-centimeter spark, you remember, requires 30,000 volts. The current in the carbon arc is usually several amperes and is highly concentrated in space. Here, most of the required free electrons evaporate out of the white-hot negative electrode, or are knocked out of the electrode by the impact of positive ions. However, ionization-by-collision in the hot vapors is also an essential feature, as it is in the spark.



Conduction in a gas. Positive ions drift toward the negative electrode; negative ions and electrons toward the positive electrode. Collisions of electrons with neutral molecules produce new ions and radiation (light).

Metal arcs, dazzling to the eyes and hot enough to melt steel, are employed in electric welding. Similar arcs often form momentarily when the switch is opened in a circuit carrying a large current.

Arcs passing through low-pressure vapors are increasingly important these days in lighting and other commercial applications. The blue-colored mercury arcs and the recently-developed bright yellow sodium street lamps are examples. The new, popular fluorescent lamp depends on an arc through mercury vapor to carry the current. The white light comes from fluorescent materials coating the wall of the tube, that are excited by the ultra-violet rays from the mercury arc. In comparison with sparks and glow discharges, all arcs, whatever their type, are characterized by relatively low voltages (usually less than 100 volts) and large currents (usually an ampere or more).

Currents that alternate very rapidly produce an interesting discharge that is related to the spark, but requires somewhat lower voltage. When the frequency is around a million oscillations per

second, the electrons and ions in the discharge oscillate back and forth in a small region and are not lost to the electrodes. As a result, discharges several feet in length are obtained with a few hundred thousand volts. You have probably seen the spectacular demonstrations in side shows and other places, where the purple-tongued, snake-like sparks are permitted to dart out and strike a metal wand held in the hand of the demonstrator. What a brave man! you thought. But curiously enough, these high-frequency currents pass harmlessly over the surface of the skin and do not penetrate into the body. Too potent a spark, striking the skin directly, will cause a burn; but, normally, a tingling sensation is the only effect. Small commercial devices, sometimes mis-labeled "Violet Ray Outfits," give this type of high-frequency spark, and are advertised to cure practically anything that ails you. You may guess for yourself how effective they are likely to be.

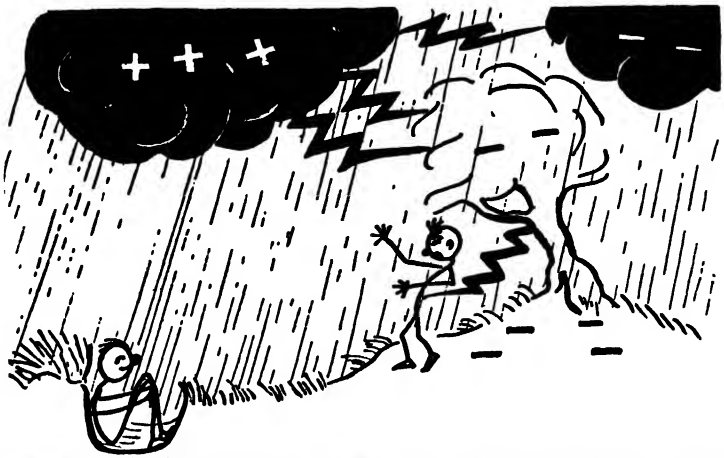
VII. *Do Lightning Rods Furnish Adequate Protection?*

Perhaps the most terrifying, but at the same time one of the most magnificent spectacles of nature is the blinding flash of lightning followed by a crashing, rumbling peal of thunder. How is it that the clouds become charged to such tremendous potentials—hundreds of millions of volts? When we talk about the weather in Chapter Ten we shall understand better the particular atmospheric conditions required. But the principle is very simple. It is just like walking across the carpet, charging your body by wiping electrons from the rug, and then discharging it by a spark to the metal radiator. Because of air currents and winds, the larger-sized water droplets in the clouds are frequently broken up. In the process they lose some of their electrons to the surrounding air, which is usually rising and thus carries the negative charge up with it. Commonly, then, the lower lying clouds made up of a larger fog or rain particles are charged positively, being deficient in electrons, while the higher clouds are negative with an excess of electrons. A flash of lightning serves to neutralize the charges when the potential becomes too great.

Sometimes the lightning jumps harmlessly from cloud to cloud or between portions of the same cloud; but when a black thunder cloud hangs menacingly overhead and begins to sink close to the earth—look out! The chances are that you won't be hit; but it is wise to keep away from high exposed spots, lone trees, iron bridges, or any other conducting pointed objects that seem to "draw" lightning

to them. You will be much safer lying down in the open, or better yet, huddling in a gully or depression. You will be perfectly safe in a steel railroad car running on grounded steel rails.

But why, then, do people put pointed metal spikes on their houses and barns for protection against lightning? It is no figment of the imagination that sparks prefer to jump to sharply curved or pointed objects. This is because charges tend to congregate densely at such places and very intense electric forces result. Such concentration of



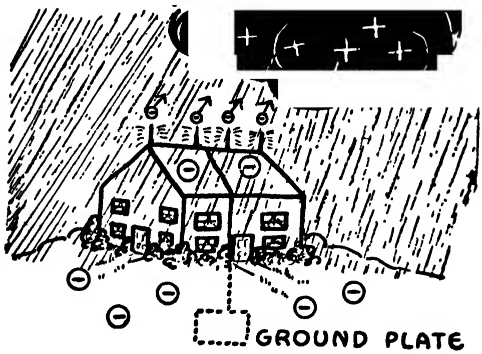
It is unwise to take shelter under an exposed tree during a thunderstorm. The man in the gully is wet but safe.

charges often causes a silent, faintly luminous leakage of current into the air, without any real spark accompanying the discharge. This phenomenon was long ago named by sailors *St. Elmo's Fire* (after the patron saint of seagoing men), because the purplish or bluish glow is often visible on the points of the masts and rigging of a ship during a thunderstorm. This eerie effect sometimes appears on land at the tips of trees or on spires of buildings. If you are familiar with x-ray equipment, you have perhaps observed a faint purplish glow around some of the high tension wires when the apparatus is operating in a dark room. This *corona* or *brush discharge,* as it is called nowadays, results in loss of power; and it is eliminated as far as possible in high-voltage equipment by using wires of large diameter and by rounding off sharp corners.

However much the designers of x-ray equipment may dislike St. Elmo's Fire it seems that there is always compensation in this world

for every evil. For this brush discharge, sometimes unaccompanied by any visible glow at all, is effective in harmlessly drawing charge from thunder clouds. Neutralization of the approaching thunder clouds in this fashion is supposed to be one of the principal functions of lightning rods.

Let us examine in detail just what happens when a highly charged cloud approaches a house fitted with sharp-pointed protectors. Suppose that the cloud is positively charged. Because of the attractive forces, free electrons are drawn to the conducting surface of the earth in the neighborhood of the cloud. The resulting negative charge concentration is greatest at the sharp points of the lightning rods. When the cloud gets close enough, the air breaks down and a corona discharge starts between lightning rods and cloud. Elec-



House protected by lightning rods. Induced charges pass off harmlessly and neutralize the cloud.

trons are then drawn to the cloud through the air, tending to neutralize the positive charge on the cloud. Even if a bolt of lightning does striken eventually, its intensity is diminished; and the network of metal conductors covering the house furnishes additional protection by shielding it and carrying the current off to ground.

Nearly everyone agrees that lightning rods furnish valuable protection for isolated buildings, but the chief cause of their effectiveness is still a subject for argument. Some authorities believe that the shielding and conducting action constitutes the principal advantage of the rods, and that there is very little discharging effect on the approaching clouds. Other authorities think just the opposite. From small-scale laboratory experiments, it appears probable that

both types of action are effective, though it is difficult to tell which is the more important.

In any case, it is necessary that the lightning rods be properly installed. A bolt of lightning may carry a momentary current of several thousand amperes. Such currents have been known to melt a heavy rod down to a shapeless mass. Hence the rods must be carefully grounded with stout cables leading to metal plates buried deep in the wet earth. Without this precaution, part of the current may travel through the building, and thus start a fire or cause injury to the occupants.

From the discussion above, you can understand why houses in the middle of a city are seldom struck by lightning. They are protected by the high spires and the many pointed objects that surround them. Likewise, it should be apparent that the old adage, "Lightning never strikes twice in the same place," might better be changed to the warning, "If lightning strikes a place once, it probably will again." It is a well-known fact that many exposed trees and buildings have been struck several times.

VIII. *When Is Electricity Dangerous?*

Lightning does strange things. It can, of course, kill people or animals and start fires. It can split trees, apparently as the result of rapid heating and expansion of sap vapors and wood, when the huge currents surge through the semi-conducting tree trunk. It can melt stout metal conductors, sometimes disrupting power and light service if the transmission lines are not carefully protected by special lightning arresters. But many stories are told of miraculous and hairbreadth escapes by individuals who have been struck, or nearly struck, by lightning.

All this brings up the question: under what conditions is electricity dangerous? and when is it harmless? Lightning is so potent and capricious that we are usually unable to predict where a bolt will strike, or what its effects will be. Man-made electric currents are, however, more amenable.

You have seen birds perched on high-tension power lines, and have had a feeling, perhaps, that if you were to sit in the same spot you would be killed instantly. But not so—not if you alighted on the wire like the birds without touching simultaneously another wire or grounded conductor. In other words, if you are to be harmed, your body must form a path for current between two points of

different potentials. The circuit must be closed. That is the first requirement for the flow of electricity. And it is the current through your body that burns the flesh and causes the shock that may stop the beating of your heart. As little as one-tenth of an ampere may prove fatal if it passes through the main part of the body. Sometimes the victim may be resuscitated by application of artificial respiration or by an injection of adrenalin—but not often.*

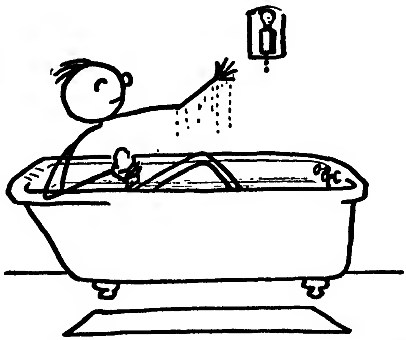
Thus, sufficient current must be available before a shock is harmful. You feel nothing more than a pinprick when your body, charged to perhaps 10,000 volts by walking across the rug, is discharged by touching a water pipe. The current in the spark is small; and the total number of electrons—that is, the quantity of charge—is insufficient to do any damage. Again, the ignition system of your automobile is not considered particularly dangerous, though several thousand volts are applied between the points of the spark plugs. If you touch the binding post of a spark plug when the motor is running, you probably will not enjoy the experience, and you will take care not to make the same mistake again. But I have never heard of such an encounter proving fatal, even when the surprised victim was in good contact with the metal frame of the car, and the current passed through his whole body. There is simply not enough current available.

"But," you ask, "if a 6-volt storage battery is able to supply several hundred amperes to the self-starter of an automobile, why can't it kill a person? Only a tenth of an ampere is required for that."

What you say is true. And yet, you scarcely feel a shock when you take hold of the terminals of a 6-volt battery. Here Ohm's Law comes into the picture: *amperes equals volts divided by ohms.* The resistance of your body, even when the best possible contact is made with the skin, is several hundred ohms. Apply six volts and what do you get? A current harmlessly small.

* One-tenth ampere is about the minimum 60-cycle alternating current to cause *ventricular fibrillation* (stopping of the heart beat) in animals such as dogs and sheep that are approximately the size of a man. Frequently, much larger currents do not prove fatal, especially if direct current is used instead of alternating, or if the current does not pass through the heart region, or if the duration of the shock is very short. In cases of ventricular fibrillation, a "counter-shock" of large current for a short time often starts the heart beating again. For further deails see the article by L. P. Ferris *et al.* entitled "Effect of electric shock on the heart," in *Electrical Engineering* for May 1936, Vol. 55, page 498.

The 110 volts in your house lighting circuit can force enough current through your body to be fatal. But even here, if you are standing on an insulating floor, you will receive nothing more than an unpleasant jolt when you stick your finger into a lamp socket. On the other hand, if you are sitting in a bath tub with your body grounded through the semi-conducting water, it may prove fatal even to reach out and turn on the light. The outside of the lighting



Danger! Don't reach out to turn on the light when you are in the bathtub!

fixture is supposed to be insulated from the power supply; but the insulation is sometimes none too good, and frequently it wears out. Don't try it.

In this same connection, it may be noted that fires are often started by faulty electric wiring. Consider a lamp cord, for example. The copper wires are insulated from each other by rubber and cloth of sufficient thickness to withstand several hundred volts when the cord is new. But rubber ages and cracks. Or the insulation may become worn by continual rubbing; so that after some years the bare metal wires come into contact with each other. If there is good contact between the bare wires, a short circuit will result (that is, a very large current will flow because of the small resistance) and a fuse will burn out.* More likely, however the contact will be poor and an arc will form and will smoulder intermittently. Such an arc is likely to go undetected until it starts a

* A fuse is a safety device containing a wire that melts at a low temperature. Excessive current heats the fuse-wire sufficiently to melt it, thus breaking the circuit and preventing further flow of current. The practice of inserting a penny under a burned-out fuse plug, rather than replacing the fuse with a new one, is very dangerous because the fuse can no longer furnish protection against a short circuit.

fire. The practice of permitting trash or scraps of metal to accumulate in contact with the wiring in your attic is especially dangerous.

IX. *How Is Electroplating Done?*

We turn now to a further manifestation of electricity; namely, the chemical effect when a current is forced through a conducting liquid by an externally applied voltage. This will lead us to an explanation of the generation of electric currents by chemical methods—that is, by means of batteries.

Many liquids, such as oils, are very good insulators. But others, such as solutions of salts, bases and acids in water, are fairly good conductors. The metals are about a million times as high in conductivity as the best liquid conductors; but these liquids are in turn billions of times as high as even the poorer insulators.

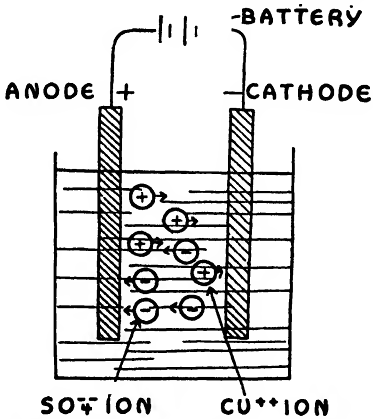
Now if a liquid is to be a good conductor, it must be like a metal in that it contains free electric charges that are ready to begin moving as soon as a small voltage is applied. In a liquid conductor, the mobile charges are not electrons, but instead are electrified atoms or groups of atoms (called *ions*, as in a gas). These ions are the result of the natural break-up of the molecules dissolved in water.

Very pure water is a good insulator, containing few mobile ions. But let us see what happens when we dissolve in it some salt like the familiar blue-crystal copper sulfate. A molecule of copper sulfate is made up of one atom of copper, one atom of sulfur, and four atoms of oxygen. Its chemical formula is $CuSO_4$. A copper atom, like any metal atom, gives up one or more of its electrons fairly easily. The remainder of the copper sulfate molecule, the so-called *sulfate radical*, has a strong affinity for electrons. As a result, some of the molecules break up into free copper ions and free sulfate ions when in solution. Each copper atom loses two of its electrons, and thus is left with a double positive charge. The symbol for this ion is Cu^{++}. The sulfate radicals, which steal the electrons away from the copper atoms, become negatively charged and are represented by the symbol SO_4^{--}.

Now let us insert two metal plates into our solution of copper sulfate and connect these plates to the terminals of a battery. The negative electrode (the *cathode*), with excess electrons on it, naturally attracts the positive Cu^{++} ions. When an ion finally wades through the resisting viscous mass of water molecules and reaches the negative plate, two electrons leave the plate and attach themselves

to the ion. Whereupon the ion, once more a neutral copper atom, simply sits down on the metal plate and attaches itself thereto. A copper atom has been *electroplated* onto the negative electrode.

But let us see what happens at the positive electrode to which the SO_4^{--} ions are attracted. When an ion arrives, it loses its two extra electrons, but it is not plated out in the form of sulfur and oxygen atoms. Instead, the neutral sulfate radical, being very active chemically, tends to react with the water and with the metal of the positive electrode so as to form another sulfate molecule, which may be soluble. The outcome of this reaction depends on the kind of metal that is used as the positive plate (called *anode*). For example, if the anode is copper, a new copper sulfate molecule is formed, and is immediately dissolved, and the whole process can repeat as before.



Copper-plating from a solution of copper sulfate ($CuSO_4$). Copper ions deposit on the negative electrode; sulfate ions pick copper atoms out of the positive electrode.

As you can see, for every copper atom that is plated out at the cathode, another copper atom goes into solution at the anode. The net result is a continuous transfer of copper atoms from the positive to the negative electrode, without any net change in the solution. Since only copper atoms are transferred from one plate to the other, copper is often purified by this electroplating process.

Not always is the solution left unchanged. For example, consider a solution of sulfuric acid—H_2SO_4, which breaks up into two H^+ hydrogen ions and one SO_4^{--} sulfate ion—with electrodes made of platinum, which resists chemical attack. When current is passed through this solution, hydrogen gas is evolved at the cathode; at the

positive electrode the neutralized sulfate radicals take up hydrogen from the water (H_2O) and the liberated oxygen atoms, which cannot react with the platinum, come out of the solution as oxygen gas. The net result, then, is the disappearance of water as it is broken up into its constituents. Pure hydrogen and oxygen are prepared commercially in this fashion.

Electroplating is an important industry. Probably you own some plated silverware. Chromium plating makes the headlights and bumpers on your automobile bright and shiny. In late years, chromium has almost completely replaced nickel plating, because it lasts longer and keeps a brighter finish. Gold-plated jewelry and plated gadgets of all kinds are in wide use.

There are many technical difficulties in obtaining uniform, long-wearing plated surfaces. In all plating processes, however, the principle is the same. An electric current deposits metal atoms on the negative electrode, just as the copper atoms were deposited in the example already described. In the case of tableware, for instance, the spoons and knives and forks themselves constitute the cathode; while plates of pure silver are used as anode. Silver atoms are carried from one electrode to the other in a solution of potassium silver cyanide. Electroplaters use this particular chemical because it happens to give a smooth, hard layer of silver over the iron base-metal. Chromium is plated in a similar manner from a warm chromic acid solution.

The passage of current through a conducting liquid has its uses, as you can see. But it can also have annoying and expensive effects. Perhaps you know that *corrosion* of metals is often the result of electrical currents. Two different kinds of metal touch each other somewhere, so that electrons can pass freely from one to the other, and both pieces of metal also touch the same conducting solution—the salty water of the ocean, for example. One of the metals is gradually eaten away, and an unwelcome deposit builds up on the other. If you are a sailor, you know that you must be careful what kind of screws you use in the bottom of a metal-hull boat. If you are a landlubber, you have probably noticed that metals rust and tarnish more readily in moist air, where a little conducting film of water can form on the surface, than in a dry place.

X. *How Does a Battery Generate Current?*

We have just seen that an electric current can effect chemical changes. Does the inverse process occur? Can chemical reactions generate current? The answer, of course, is *yes*. Every battery is

a container of chemicals wherein chemical energy is transformed into electrical energy while the battery is being discharged. In some types of batteries the chemicals can be restored to their original condition by reversing the process, sending electrical energy into the battery. These, for obvious reasons, are called storage batteries. Other types, such as the familiar dry cells, can be discharged only once, and must then be discarded—in these the chemical processes can also be reversed by reversing the current flow, but the chemicals are not restored to their original positions in the cell, so the cell is not the same as it was before.

To understand the action of batteries, let us talk about a very simple sort of cell: a zinc plate and a copper plate immersed in a solution of copper sulfate. There is a potential difference of about one volt between the copper and the zinc. The copper is positively charged, the zinc negatively charged, and if we connect a wire externally between the plates, electrons will flow continuously through the wire from the zinc to the copper.

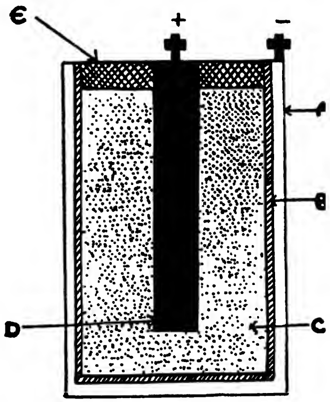
Here is what happens inside the cell. Copper ions, Cu^{++}, come out of solution and attach themselves to the copper plate, charging it positively. At the same time, zinc ions (Zn^{+}) leave the zinc plate and go into solution, leaving the zinc plate negatively charged. Before the two plates are connected by an external wire, the copper plate is charged up just so positively that no more Cu^{++} ions can get to it, and the zinc plate is charged just so negatively that no more Zn^{+} ions can leave it. When the plates are connected externally, current through the external circuit tends to make the copper more negative, and the zinc more positive, than they were before. But this tendency is opposed by the chemical actions in the cell: the copper cannot become much more negative so long as it can receive Cu^{++} ions from the solution, and the zinc cannot become much more positive so long as it can give up Zn^{+} ions to the solution. The current flows, in fact, until the zinc plate is eaten away as zinc sulfate is formed.

The reaction can be reversed: if current is passed through the cell in the opposite direction, Zn^{+} ions plate out on the zinc electrode, and Cu^{++} ions go back into solution from the copper electrode. The redeposited zinc metal, however, is spongy and adheres to the plate only poorly, so this cell is not a practical storage battery.

If you ask why all this goes on—why copper ions are eager to leave the solution and zinc ions are eager to enter it—I shall be at a

loss for a simple answer. The difference goes back, of course, to differences between the electronic structures of zinc and of copper atoms, but it is an involved business to reason from the structure of the atoms to the behavior of the cell. Only in the last few years has the connection between them begun to appear even reasonably clear, and the theory still is hazy in some of its details.

For many reasons, the dry cell has come to be the most widely used of the non-rechargeable batteries. It consists of a carbon rod electrode, positive, and a cup-shaped zinc electrode, negative, which also serves as a container for the rest of the cell. The electrolyte is a pasty mixture of several chemicals, the essential one being ammonium chloride (sal ammoniac). Thus a dry cell is *not* actually dry.



The construction of a dry cell. (*A*) Zinc jacket. (*B*) Porous paper. (*C*) Paste of sal ammoniac and other chemicals. (*D*) Carbon rod. (*E*) Sealing wax.

It will fail to give current once the chemical mixture is either dried out or used up. A new dry cell will maintain a voltage of about one and a half volts, and can deliver a current as high as 30 amperes if short-circuited. The short-circuit current, however, will rapidly fall to a low value, because hydrogen bubbles collect on the carbon electrode and decrease its effective area, thereby increasing the internal resistance of the cell. The cell in this condition is said to be *polarized;* if it is allowed to rest for a time, this hydrogen is absorbed by one of the chemicals (manganese dioxide) and the cell can again furnish a large short-circuit current. As the cell gets older it gradually deteriorates, either by loss of moisture or by the using up of the zinc electrode. Its voltage stays nearly the same during life, but

the current it will support goes down, because the internal resistance becomes high.

So-called *B-batteries* used in battery radios are simply a large number of small dry cells connected together and packed into a single container. The cells are connected in *series* (with the positive carbon electrode of one attached to the negative zinc case of the next); the total voltage is the sum of the voltages delivered by the separate cells. A 45-volt B-battery contains about 30 small-sized dry cells.

In dry cells, as in chemical batteries generally, the voltage between the electrodes when they are not connected depends only on the materials used in the cell, and is independent of the size of the cell. On the other hand, the maximum current that can be drawn depends on the internal resistance of the cell. If the cell has large electrodes near together, and if the electrolyte is a good conductor, the internal resistance will be low and the short-circuit current will be correspondingly high.

When you want a battery that can be recharged, you are likely to get a lead storage battery, such as is used in your automobile. Other types of storage batteries, such as the Edison battery, are available on the market, but have not found very wide application for everyday use. In the lead storage battery, the positive plates are lead oxide, and the negative plates are lead. The liquid is sulfuric acid diluted with water. Each cell supplies about 2 volts, and the ordinary 6-volt battery contains three cells connected in series. Currents of several hundred amperes may be drawn for a few seconds, as when a self-starter cranks a cold automobile engine. But it does the battery no good to hold the starter button down continuously for half a minute or more when the engine refuses to catch hold.

The chemical reactions in a lead storage battery are numerous and involved; but on discharging, lead sulfate always appears on both electrodes, while sulfuric acid is used up. On charging, the lead sulfate disappears and the acid is re-formed. Hence, the condition or state of charge of the battery can be measured by the specific gravity* of the liquid. Sulfuric acid is heavier than water, and

* *Specific gravity* is defined as the ratio of the weight of a given volume of any material to the weight of an equal volume of water. Thus, the specific gravity of oil is about 0.8, because a quart of oil weighs about 0.8 as much as a quart of water. The specific gravity is measured by a device called a *hydrometer*. The floating hydrometer bulb sinks deeper, the less the specific gravity of the liquid in which it is immersed. This action is explained by *Archimedes' Principle*, discussed in Chapter Four.

when the battery is fully charged, the hydrometer reads about 1300. This means that the specific gravity of the acid is 1.3. A completely discharged battery, containing only water and no sulfuric acid, would have a specific gravity of 1.0. It is usually considered wise to recharge the battery by the time the specific gravity has been reduced to 1.2 or a little less—the recommended limit varies with different makes of batteries, and with the temperature.

Instead of single plates of lead and lead oxide in a cell, it is customary to use several of each, separated by wood or porous-rubber spacers. This scheme makes available greater currents (because of the increased plate area) and a larger *ampere-hour capacity*. Essentially, the ampere-hour capacity is a measure of the chemical energy that is stored up in a cell and is available for transformation into electrical energy when the battery is discharged. A good 13- or 15-plate cell may have a capacity of more than 100 ampere hours—which means that it will supply a current of one ampere for 100 hours, or if you wish, 2 amperes for somewhat less than 50 hours, or 10 amperes for considerably less than 10 hours. It would not furnish 100 amperes for even nearly one hour, because such a large current would cause the plates to buckle, and the battery would be ruined long before the hour was up.

CHAPTER SIX

MAGNETISM AND SOME OF THE APPLICATIONS OF ELECTRICITY

I. *What Is Magnetism?*

Electricity is versatile. We have discovered already that with it we can conjure up such effects as *force* (between static charges), *heat, light, chemical action,* and even, somewhat indirectly, *sound.* This is a formidable array of talents for any phenomenon to exhibit. But have we missed anything? Does an electric current manifest itself in any other fashion?

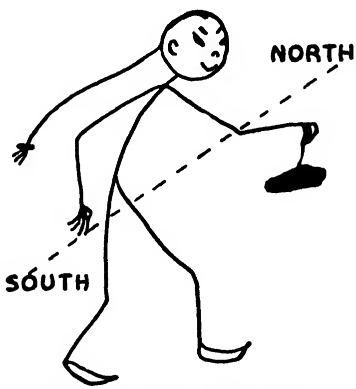
Yes, it does—as we can demonstrate by a very simple experiment. Hang a pair of wires up side by side, and through each of them send a current in the same direction. Will you be surprised to find that the wires are attracted to each other? In one of the wires, now reverse the direction of the current. The wires will be mutually repelled instead of attracted.

Here is something unexpected. The force between the parallel wires carrying a current cannot be due to static charges because there is no excess charge, either positive or negative, on either wire. There is merely a flow of electrons. Furthermore, reversing the direction of the current in one of the wires reverses the direction of the force. All this behavior is the result of *magnetic* effects, associated with the electric current.

The phenomenon of magnetism was known to the ancients many centuries before anyone dreamed of such a thing as an electric current. Long before the Christian era, the people of Asia Minor and Egypt knew that natural magnets, or loadstones (the mineral *magnetite,* an oxide of iron), attracted bits of iron. The Chinese claim to have been the first to discover that a loadstone could be used as a compass needle. In the Western world, the compass had won an accepted place as a necessary aid to navigation, late in the Middle Ages. By the year 1600, William Gilbert, a physician to Queen Elizabeth, had placed the subject of magnetism on a sound scientific basis. But not until 1800, when Volta invented the chemical battery, were sizeable electric currents available to experimenters. And

it was another 19 years before Oersted, while lecturing to a physics class at the University of Copenhagen, happened to place a compass needle near a wire carrying a current and discovered that the needle was deflected. Thus, accidentally, in the year 1819, was it found that magnetism is linked with electricity. On this linkage depends the operation of our modern motors, generators, transformers, and countless other devices.

Before discussing these complicated matters, let us review some of the simpler facts about magnets and magnetism. Doubtless you know already that magnets always have two poles; that like poles repel each other and unlike poles attract each other; that pieces of iron are magnetized by induction when brought into the neighbor-

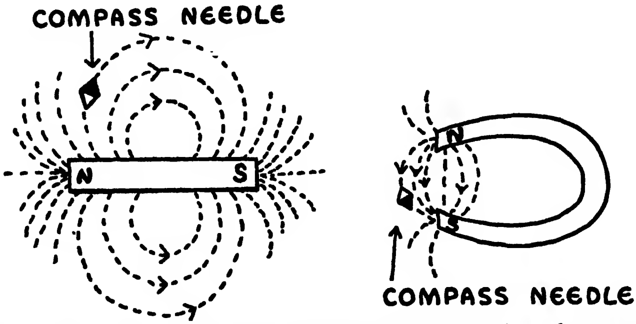


The Chinese are supposed to have invented the magnetic compass.

hood of magnets; that, although soft iron readily loses its magnetism, steel may be permanently magnetized; that the earth acts as though it contained a huge magnet and compass needles thus point approximately north and south.

Let us examine in more detail some of these properties of magnets. Suppose we place a small, permanently magnetized compass needle near a larger steel bar magnet. The compass needle will set itself in a definite direction, with its north-seeking pole (the end usually painted black) tending to point toward the south pole of the large magnet, and with its south pole tending to point toward the north pole of the magnet. Since it is surrounded by a considerable region in which other magnets are affected, we say that the large magnet has a *magnetic field* around it. The direction of the field

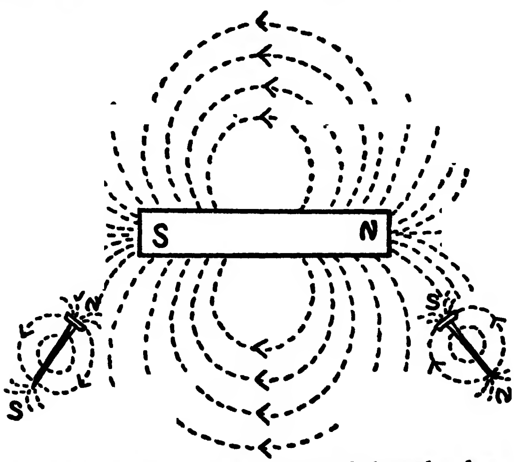
at any point is identical with the direction in which the small compass needle sets itself; and the stronger the field, the greater the force on the poles of the small magnet. We can map out this field, repre-



Magnetic fields in the neighborhood of a bar magnet and a horseshoe magnet. A small compass needle sets itself parallel to the lines of force.

senting it by lines—called *lines of force*—that are wholly imaginary but serve to indicate the direction of the field at any point. The density of these lines pictures the strength of the field.

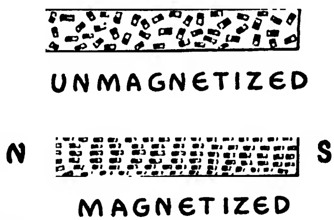
We have seen that a small permanent magnet such as a compass needle will set itself parallel to a magnetic line of force. But an unmagnetized piece of soft iron will do the same thing, and will, furthermore, be attracted to the pole of a permanent magnet just



Magnetism is temporarily induced in soft-iron nails brought close to a permanent magnet. The nails are attracted to the poles of the magnet.

as is a compass needle. Suppose that a nail, for example, is brought near the south pole of a permanent magnet. A north pole is ***induced*** in the nail on the end nearer the south pole of the magnet, and a south pole is induced on the other end of the nail. The nail becomes temporarily a magnet; but it loses most of its induced magnetism as soon as it is removed from the field of the permanent magnet.

Nearly all materials have weak magnetic properties that can be detected and measured by delicate apparatus. But a very few materials—iron, cobalt, nickel, and several alloys—show outstandingly large magnetic effects. These ferromagnetic substances, as they are called, are essentially different from the common run of materials. They naturally contain a multitude of tiny magnets, which are normally pointing in all the various directions so that their individual magnetic effects cancel out. When the material (the iron nail we were talking about, for example) is placed in a magnetic field, all the tiny magnets in it turn about and tend to line up with the field, and so with one another. As a result, the sample is itself a good magnet, as long as it is in the magnetic field. Once it is removed,



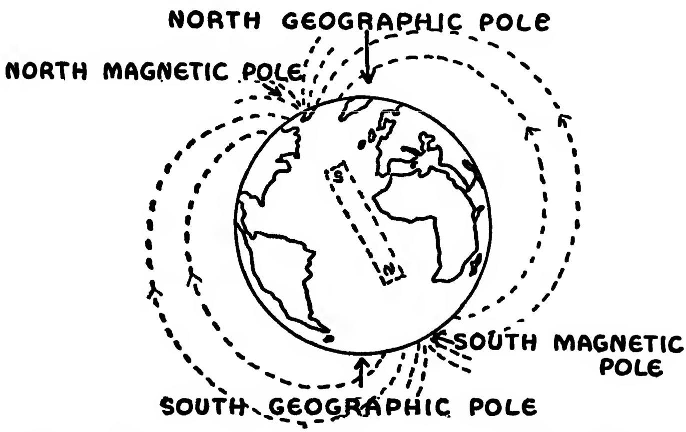
In an unmagnetized piece of iron, the elementary atomic magnets are arranged in higgledy-piggledy fashion. When the iron is magnetized, the atomic groups are lined up.

the tiny magnets again become disorganized, and the sample no longer acts as a magnet.

Permanent magnets are also made of ferromagnetic materials, but various tricks are employed to keep the tiny elementary magnets in them from getting out of alignment, once they have been lined up in a magnetic field. In steel, for example, the elementary magnets are brought into cooperation only with difficulty, but they also find it hard to get out of line with one another after the magnetizing field is removed, and a permanent magnet is the result. Even a steel magnet, however, will lose its magnetism if it is heated or severely jarred. In recent years certain alloys (notably one called ***Alnico,***

containing aluminum, nickel, and cobalt) have been used to make extremely powerful permanent magnets.

If you ask why iron, nickel, and cobalt naturally contain these tiny magnets, while gold, lead, and the other metals do not have them, I shall have to say that no one yet has a very satisfactory answer. The electrons in a metal are continually travelling about, and moreover each electron continually whirls, teetotum-fashion. Both of these motions constitute electric currents, and the magnetic effects of these currents are presumably responsible for the magnetic behavior of the material. In fact, the weak magnetic properties of ordinary materials can be explained quite acceptably by considering



The earth acts as though it contained a huge magnet, though the actual cause of the earth's magnetism is unknown. Note that the earth's north magnetic pole is really what we term a south pole; that is, a *south-seeking* pole. Likewise, the earth's south magnetic pole is a *north-seeking* pole.

in detail how these electron currents will interact with external magnetic fields. The ferromagnetic metals are more of a puzzle. How the travelling and spinning electrons in them cooperate to produce the tiny magnetized domains is beginning to be understood, but the picture is not yet complete.

The magnetism of the earth remains essentially unexplained, despite the many theories that have been advanced. The magnetism of both sun and earth appears to be connected with the rotation of these bodies. For many reasons it seems unlikely that the earth actually contains a large iron magnet. But why are the earth's magnetic poles not located at the geographic poles? And why do the mag-

netic poles gradually shift their positions with the passage of the years? At present the north magnetic pole (that is, the place where a compass needle points vertically downward) is located north of Hudson's Bay, well over a thousand miles from the north geographic pole. It is moving to the westward at the rate of a very few miles per year. The south magnetic pole is in the antarctic, nearly opposite the north magnetic pole.

The behavior of the earth's magnetic poles is not only mysterious, but most annoying. Compass needles fail to point to the true north, and what is worse, their error, or *declination,* changes slightly from year to year in any one locality. In Maine the compass points as much as 23° to the west of true north,* and in the state of Washington as much as 24° to the east of true north. There is one line in the United States (extending irregularly from South Carolina northward through the middle of Lake Superior) where the compass does point to the true north; but east or west of this line the declination varies between 0° and the maximum of 23° or 24°.

Other minor irregularities and temporary variations in the earth's magnetic field add to the unreliability of compass needles. Some of these irregularities are due to the proximity of masses of iron ore or other bodies of magnetic material—perhaps meteorites buried in the earth. The temporary variations are often connected with sunspot activity. Frequently these *magnetic storms* are accompanied by various other phenomena, such as poor radio reception and unusual auroral displays.

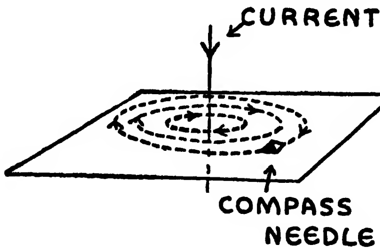
II. *How Do Electromagnets Work?*

Since electric currents are presumably responsible for all magnetic phenomena, it follows that a wire carrying a current might be expected to have a magnetic field associated with it. Such is found to be the case. If we plot out this field with the aid of a compass needle, we find it quite different in shape from the field around a magnet. The lines of force are concentric circles with the wire at the center. The field becomes weaker, of course, as we get farther away from the wire.

The magnetic field associated with a current of a few amperes is comparatively feeble. Its strength is normally less than one one-hundredth that of even a weak permanent magnet. But suppose we

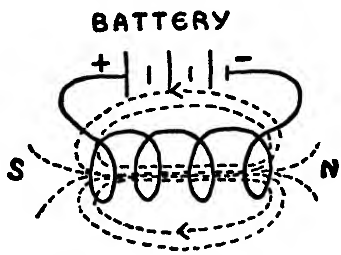
* You recall that a whole circle is divided into 360 degrees. A right angle is therefore 90°, and 23° is about a quarter of a right angle.

wind the wire up into a coil of, say, 100 turns. Then the field due to each loop of wire adds to the field of the other loops. In effect, we have multiplied the field due to the single wire by a factor of 100; and this has been accomplished without increasing the original current. Furthermore, the field due to a coil is essentially not different in shape from the field surrounding a bar magnet. A coil



The magnetic lines of force surrounding a current-carrying wire are in the form of concentric circles.

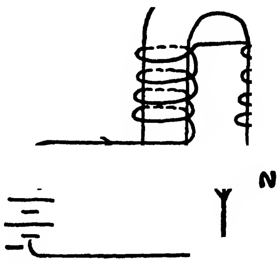
wound in the form of a helix or solenoid (so that it looks like a screen-door spring) exhibits polarity just like a bar magnet, and if free to swing will line itself up parallel to the earth's magnetic field, pointing north and south. If the direction of the current is reversed, the polarity of the coil is reversed.



The magnetic field due to a coil of wire carrying a current is much like the field of a bar magnet.

Suppose we insert a bar of iron into a helix that is carrying a direct current. We shall find that the iron has become a powerful magnet and that the field at the ends of the bar has become hundreds of times stronger than the field of the helix alone. The iron bar has become magnetized by induction, and in doing so has greatly augmented the original field. We have an electromagnet.

If we do not want our electromagnet in the shape of a straight bar, there is no great difficulty in bending the iron into the form of a U or horseshoe, and then winding coils on each arm. This scheme brings the north and south poles into close proximity and makes the magnet even more powerful. Large electromagnets of essentially this design are frequently employed to move scrap iron and steel. Hundreds of pounds at a time are lifted by the powerful magnets. If the magnet is placed on a crane, the scrap iron may be conveniently dropped in any desired place by simply shutting off the current in the coils.

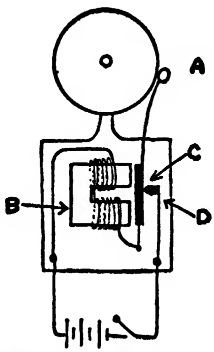


One form of electromagnet: current-carrying coils wound on a U-shaped soft-iron core.

Now let us consider one very common electromagnetic device—the ordinary doorbell. This neat little machine may be found, in slightly modified form, serving as a magnetic relay or switch, as a plain buzzer, or as a make-and-break in a spark coil—to name only a few of its applications. Its operation is simple. A U-shaped electromagnet attracts to its poles a strip of soft iron, called the *armature.* The bell clapper is attached to the armature, and the armature in turn is mounted on a piece of spring steel. When there is no current in the coil, the spring holds the armature away from the magnet; but when the circuit is closed, the armature is attracted to the magnet, and the clapper clangs against the bell. There would be only a single clang if it did not so happen that the armature automatically breaks the circuit as it moves toward the magnet. Once the current ceases, the armature is no longer attracted, and immediately springs back to its rest position. Whereupon, the circuit is closed once more, the armature is again attracted to the magnet—and so on, indefinitely. All this takes a long time to tell; but, as

you well know, the motion is very rapid, with the clapper setting up a loud and continuous clatter as it beats on the gong with each oscillation.

All this talk about magnets and electromagnets naturally brings up the subject of the magnetic mines which were so widely discussed in the newspapers early in the war. A steel ship, in the earth's magnetic field, becomes magnetized by induction and is in effect a weak but large bar magnet. The mine contains a compass needle which turns when the magnetized ship passes over it and so closes a switch and starts the machinery that finally causes the mine to explode. To combat this weapon, the ship can be surrounded by a coil of wire



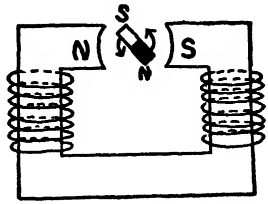
The electric doorbell. (*A*) Bell and clapper. (*B*) Electromagnet. (*C*) Soft-iron armature free to oscillate on a spring mounting. (*D*) Make-and-break contact.

(a "de-gaussing belt") carrying an electric current; if the direction and size of the current in this electromagnet are adjusted properly its magnetic field will just cancel the field of the ship alone, and the compass needle in the mine will then not be affected when the combination passes overhead.

III. *Why Does an Electric Motor Run?*

The electric motor is another device that depends on electromagnets for its operation. We might transform our doorbell into a motor by simply attaching the clapper to a connecting rod and crankshaft. But there are simpler and more efficient ways of changing electrical energy into mechanical energy. Suppose we replace our soft-iron armature by a permanent bar magnet and then mount this new armature on a shaft in such a way that it can rotate between the poles of an electromagnet. You might expect that, like

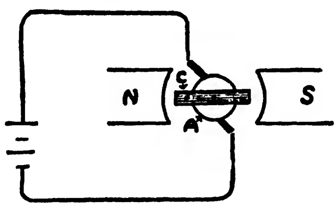
a compass needle, the armature would simply line itself up in the direction of the field and come to rest. So it would. But suppose that we change the polarity of the electromagnet just at the instant the armature swings into line with the field. Then the armature



Principle of one form of electric motor: rotating magnet turns until it sets itself parallel to the field of an electromagnet.

will have to keep right on rotating to line itself up with the new direction of the field. But suppose by the time it gets in the new position, we have again reversed the field. As this reversal occurs again and again, the armature is required to keep right on turning, always trying to catch up with the alternating field.

Perhaps you wonder how it is possible to reverse the field of our motor just at the crucial moment in each half revolution of the armature. Obviously, we cannot stand by and throw a switch several times each second to reverse the current in the coils of the electromagnet. We can, however, provide an automatic switching device with the aid of brushes and a commutator attached to the rotating shaft. Or, better yet, we can supply a source of alternating current, such as we have in our house circuit, which automatically changes



Elements of a direct-current motor. (*A*) Commutator and brushes. (*C*) Rotating coil. *N* and S are poles of an electromagnet.

its direction many times each second. Then, no commutator is needed.

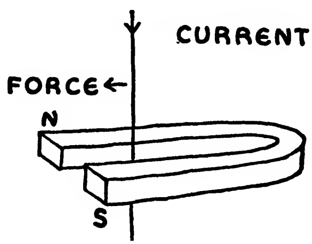
If we wish to construct a more powerful motor, why not increase the force of rotation by making the armature itself a powerful elec-

tromagnet? We might even arrange to reverse the current in the armature itself rather than in the field coils at each half revolution. These devices and many others are used in practice.

We cannot go into the numerous variations that engineers have employed in designing electric motors. But all motors operate on the same simple principle: a magnetic armature, free to rotate, starts to line itself up parallel to a magnetic field; but just as it is about to accomplish this, the field changes in direction or the polarity of the armature itself is reversed. So the armature is forced to continue its rotation as it tries to catch up with a field that is always one jump ahead.

IV. *How Are Electrical Quantities Measured?*

In discussing electric motors, we might have adopted quite a different viewpoint. Instead of describing the forces between magnets and magnetic fields, we could have stressed the forces exerted on electric currents by magnetic fields. Back at the beginning of this chapter we said that the force between two current-carrying paral-



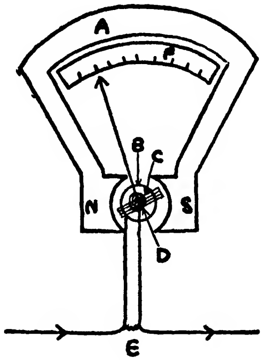
Wire carrying a current is forced sideways in a magnetic field.

lel wires was due to magnetism. More specifically, the field produced by the current in one wire exerted a force on the other wire.

This reaction between currents and magnetic fields may be demonstrated even more directly. Let a wire hang vertically between the poles of a horseshoe magnet. When the current is turned on, the wire will be forced either outward from between the poles, or inward, depending on the direction of the current and the polarity of the magnet. Perhaps this effect is somewhat surprising. But imagine the wire wound up into a coil and inserted between the poles of the magnet. The coil would rotate until its plane was perpendicular to the field of the magnet. This is only what we should

expect; for, if we inserted a bar of iron into the coil, the iron, we know, would become magnetized and would immediately line up with the field. The coil, with or without an iron core, is equivalent to the armature of a motor. So it all amounts to the same thing in the end. Now, we are emphasizing the force exerted on the wire of the armature coil rather than on the iron core.

When a wire carrying a current is located in a magnetic field, the force on the wire is proportional to the current and to the strength of the field. It is only natural that we should take advantage of this fact to measure currents. The best ammeters are quite similar in design to electric motors—only more delicate. In an ammeter, an armature coil rotates between the poles of a magnet; but the coil,



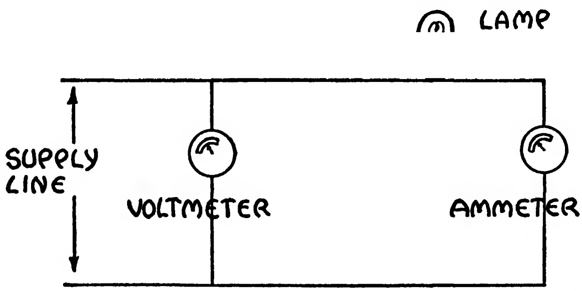
An ammeter. (*A*) Permanent magnet. (*B*) Soft iron core to make magnetic field more uniform. (*C*) Coil wound on armature. (*D*) Restraining spring. (*E*) By-pass or shunt to carry most of the current. (*F*) Scale divided to read in amperes.

being held in check by a spring, is allowed to turn through only a small angle. The greater the current in the coil, the greater the force, and therefore the greater the angle of rotation against the restraining spring. The deflection is measured by means of a pointer attached to the armature. The scale under the pointer reads directly in amperes. Cheaper and more rugged, but less accurate instruments are frequently constructed with a stationary coil and a pivoted permanent magnet as armature. The ammeter on your automobile dashboard is probably of this latter type.

A voltmeter is very similar to an ammeter. Its deflection, like that of the ammeter, is proportional to the current flowing through the armature coil. But according to Ohm's Law, *volts* equal *am-*

peres times *ohms.* Therefore, the voltage is proportional to the current, and the scale may be made to read in volts rather than in amperes.

There is one important difference, however, between a voltmeter and an ammeter. A voltmeter must have very high resistance, because it is permitted to draw only a very tiny current which will not disturb the remainder of the circuit. By contrast, an ammeter is required to have a low resistance, since all the current must pass through it. In actual use, the ammeter is placed in series with the rest of the circuit, while the voltmeter is placed in parallel with that part of the circuit where the voltage is to be measured.



Measuring the current and voltage of a lamp. The ammeter is placed in series with the lamp, the voltmeter in parallel.

In addition to instruments for measuring current and voltage, there are also devices for measuring electric power and energy. You recall, from our discussion in Chapter Two, that energy is the capacity for doing work, while power is the rate at which energy is supplied or work is done. This same distinction holds for electrical energy and electrical power. The electrical energy delivered to a device such as a motor or a toaster is proportional to the quantity of electricity sent through it and to the voltage maintained between its terminals. The quantity of electricity, in turn, is equal to the product of the current and the time the current is flowing. Putting these things together:

$$\textit{Energy} = \textit{voltage} \times \textit{current} \times \textit{time}$$

Power, the rate at which energy is supplied, is simply:

$$\textit{Power} = \textit{voltage} \times \textit{current}$$

For measuring power, the *watt* (named after James Watt, of steam engine fame) and the *kilowatt* (1000 watts) are convenient and common units. The watt is so chosen that

$$\textit{Power in watts} = \textit{volts} \times \textit{amperes}$$

The watt is, of course, the same kind of unit as the horsepower, which we defined earlier as 550 foot-pounds per second. One horsepower (it turns out) is 746 watts—with one watt of power a one-pound weight can be raised one foot in a little less than a second and a half. You may be interested in calculating either the power used, or the current flow, in some of the electrical devices in your home. The name plate usually states the voltage for which the device is designed, and either the rated current or the power required. Thus, a motor rated at 3 amperes on the 110 volt circuit uses up electrical energy at the rate of 3×110 or 330 watts—its power input is 330 watts. A 60-watt lamp takes a current of 60/110 or 0.55 amperes.

Instruments for measuring power (called *wattmeters*) are not very common outside of laboratories. The wattmeter is a sort of combination ammeter and voltmeter, reading directly the product *amperes* $\times$ *volts*, or *watts*.

The meter installed in your house, and read once a month or so by the power company, measures not power but total electrical energy supplied—the company is, of course, more concerned with how much energy you use than with how fast you use it. The unit of energy is a unit of power multiplied by a unit of time: watt-second, watt-hour, and *kilowatt-hour* are all units of electrical energy, the last one being most commonly used. Let us calculate, as an example, the energy in kilowatt-hours consumed in a month by a 100-watt lamp, operating 5 hours per day. One hundred watts is 100/1000, or 0.10, kilowatts. Five hours per day for 30 days totals 150 hours. Hence the total energy is 0.10×150, or 15, kilowatt-hours. If you pay 4 cents per kilowatt-hour for electrical energy, it costs you 4×15, or 60, cents a month to operate that lamp.

Your house meter which registers kilowatt-hours must evidently measure the power and automatically multiply this quantity by the time. Though this requirement sounds complicated, the meter is nothing more nor less than a small electric motor. This motor is designed so that the speed of rotation of the armature is proportional to the rate at which energy passes through the meter into the house;

and the total number of revolutions of the armature is then a measure of the product of the speed multiplied by the time, or electrical energy consumed. Through a gear arrangement, the armature shaft is connected to dials which record kilowatt-hours.

While we are on the subject of energy consumption, it might not be amiss to say a word about the efficiency of electrical devices. Heating appliances are practically 100 per cent efficient. Barring the negligible quantity of light emitted, all of the electrical energy consumed in the heater is transformed into heat energy. Hence the statement made back in Chapter One, that any 500-watt electric heater must give you the same quantity of heat as any other. Devices like electric irons and electric toasters may waste heat if they are poorly designed; that is, a large fraction of the energy may be dissipated into the air, and thus fail to serve the purpose for which it was intended. Nevertheless, in any such device, nearly all the electrical energy is eventually converted into heat.

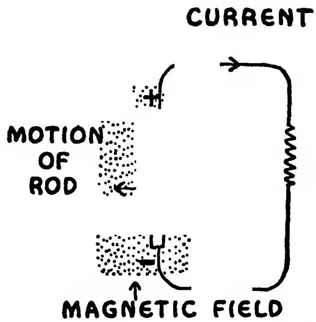
Electric motors are less efficient. Some very large motors convert over 90 per cent of the electrical energy input into useful mechanical work. By comparison, steam and gasoline engines usually have an efficiency of only 10 to 20 per cent. However, our small household-appliance motors are likely to be less than 50 per cent efficient. The rest of the power is wasted as heat. Electric lights are the least efficient of our common electrical devices. As we shall see in the next chapter, there are various ways to calculate their efficiency; but even the most optimistic method of calculation indicates that no more than 10 to 15 per cent of the electrical energy is converted into light energy. The more conservative calculations indicate a yield more like 2 or 3 per cent for an ordinary incandescent lamp. As in the case of a motor, the lost energy is dissipated in the form of heat.

V. *How Is Electricity Generated?*

Let us now digress temporarily from matters involving the consumption of electrical energy, to consider a few of the many methods available for generating electric currents. We have seen that currents can produce chemical effects, and that the process is reversible —batteries generate electricity by means of chemical reactions. But how about the other manifestations of electricity—heat, light, sound, magnetism, mechanical force? Can they too be used to generate electrical currents? The answer is that they can. Nature is pretty

obliging that way. Almost any form of energy can be converted, more or less directly, into any other form. Unfortunately, in many cases the transformation is highly inefficient.

However, with the aid of magnetic effects, dynamos are able to convert mechanical energy into electrical energy with a loss of only a few per cent. The principle is simple: a potential difference is generated between the ends of any rod or wire that is pulled through a magnetic field in such a way that the rod cuts across lines of force. In other words, electrons pile up at one end of the rod, leaving an excess of positive charge at the other end. If the ends are connected by a wire to close the circuit, current will flow. When we stop and think about it, this piling up of charge on the ends of the rod is only what we should expect. For the metal contains free electrons that



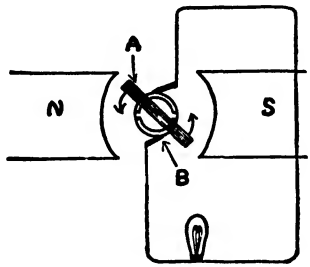
Principle of the dynamo. Dots represent magnetic lines of force directed out of the page. Electrons are forced to the bottom of the metal rod as it cuts across the lines of force.

move across the magnetic field with the rod. But this motion of the electrons is entirely equivalent to a current. And a current, we know, is forced sideways when it is placed in a magnetic field. Hence the electrons are forced to one end or the other of the rod, depending on the relative direction of the field and the motion of the rod.

A single wire moving across a magnetic field would be a clumsy generator; furthermore, the induced voltage would be very small. In practice, we again resort to our old trick of winding the wire up into a coil and mounting the coil on a shaft in such a way that it may be rotated between the poles of an electromagnet. Then the voltage induced in each loop of the coil adds to that induced in the

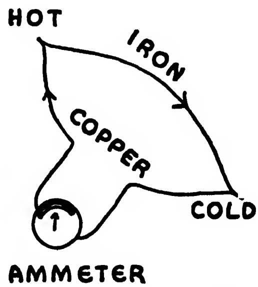
other loops. Current is brought out of the armature to the external circuit by attaching the ends of the coiled wire to commutator segments or slip rings.

By now you are probably thinking that this dynamo is in no way different from an electric motor. In principle, you are right. Any



In a real dynamo, a coil rotates between the poles of an electromagnet. (*A*) Rotating coil. (*B*) Commutator (or slip-rings) and brushes.

motor may be used as a generator simply by rotating the armature. In actual practice, however, a machine designed as a motor does not make a very efficient generator, and the construction of the two types of machines differs in detail.



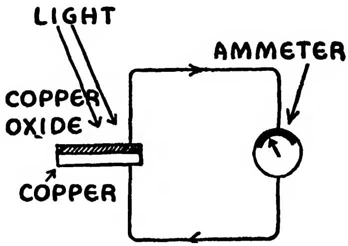
A thermocouple. Current flows in the circuit made up of two dissimilar wires when one junction is hotter than the other.

Batteries and dynamos, being the most efficient generators, supply nearly all of our electric power. But for special purposes, heat, light, and sound are very useful producers, too.

In order to convert heat directly into electrical energy, we need only take two wires of dissimilar metals (say, one wire of copper and one of iron), twist the ends together to make a closed circuit, and then heat one of the junctions. If we cut one of the wires and insert

an ammeter in the circuit, we shall find that current is flowing. The device is known as a *thermocouple.* Since the voltage generated is dependent on the difference of temperature between the junctions of the dissimilar wires, such thermocouples are often employed in laboratories as thermometers. They measure a wide range of temperatures very accurately—from the lowest temperatures up to the melting point of the wires.

Thermocouples have not found much application outside of laboratories and industrial plants. But *photoelectric* cells, which generate electric currents by means of light, are used extensively in a variety of common devices. In one type of photo-cell, the light propels electrons from a layer of one material (usually copper oxide or selenium) across to a layer of another material (copper); and



A Photronic cell (exposure meter) generates a current which varies with light intensity.

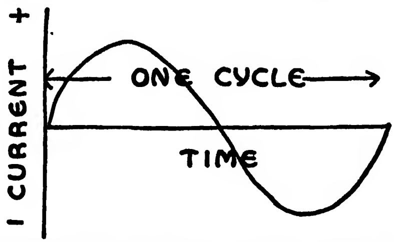
current flows continuously when the dissimilar sheets of material are joined externally by a wire. Since the current increases as the light shining on the cell becomes brighter, these cells are very useful in measuring light intensity. They are now sold as exposure meters to photographers and candid camera fans. Lighting engineers find these meters convenient for determining whether enough light is being supplied in homes, schools, and other places.

Sound, too, is useful in generating currents; though it acts in a less direct way than do heat and light. As we shall see in Chapter Eleven, sound is a vibratory or wave motion travelling through the air. One modern type of radio microphone generates electricity within itself when the sound vibrations impinge upon it. Certain mineral crystals (notably Rochelle salt and quartz) exhibit electrical charges (plus and minus) on their ends when they are compressed or stretched. This phenomenon is known as the *piezoelectric effect.* Very crudely, you may think of electrons as being squeezed out of

one part of the crystal into another part by the application of pressure. The sound vibrations are essentially variations in pressure, and thus generate minute voltages as they impinge on the Rochelle-salt crystal contained in the microphone. These tiny alternating voltages must be amplified by the broadcast equipment to millions of times their original intensity. However, the crystal microphone reproduces the fluctuations in the sound waves with greater fidelity than does the old type carbon microphone, which works on a different principle.

VI. *How Is Electric Power Distributed?*

We have spoken frequently of direct currents and alternating currents without distinguishing between them in any precise fashion. In the case of a direct current, as you might suppose, electrons flow steadily in one direction through the circuit. But in the case of an alternating current, the electrons travel back and forth, moving first in one direction and then in the other, never getting very far from their original positions. In our house-lighting circuits, 60



Graph showing how an alternating current varies with time.

vibrations, or, as we say, 60 *cycles* per second has become the standard frequency in most parts of the country.* It is convenient to standardize in this fashion, because many electrical appliances such as clocks and induction motors must be designed for a particular frequency; and they will not operate satisfactorily on any other frequency.

You might wonder why engineers have chosen quite generally to supply us with alternating current rather than direct current. In the first place, a dynamo naturally generates alternating current. You can understand why this should be. The wires of the armature

* In some sections 25-cycle and 50-cycle currents are used. Direct current is still supplied in a few places, notably in local districts of some big cities, such as Boston and New York.

coil rotating in the magnetic field cut across the field first in one direction; then, during the next half-revolution, they sweep across in the opposite direction. In between each half revolution, while the plane of the coil is perpendicular to the field, the wires are momentarily cutting no lines at all; and the induced voltage drops to zero. Hence, in one revolution of the armature, the current flows first in one direction, stops, flows in the opposite direction, stops again. One complete cycle results from each revolution of the armature coil. Now this alternating current may be rectified (changed into direct current) by leading it out to an external circuit through a commutator and brushes. But the generator may be made simpler and more rugged if it is designed as an alternating current machine with the elimination of the commutator.

A second rather minor reason for the use of alternating current lies in its adaptability to household and commercial appliances. In heating and lighting, direct and alternating currents are equally efficient, and are, in fact, usually interchangeable. Radios may be designed to operate on either A.C. or D.C. However, alternating current induction motors are simpler and more trouble-free than are direct current motors; and electric clocks will keep accurate time only if supplied with alternating current of constant frequency.

From what has been said so far, you might think that alternating current has little advantage over direct current. But actually there is a very good reason for using A.C.: alternating voltage can be stepped up or down at will by means of simple and extremely efficient transformers. There is no easy way to increase or decrease the voltage in a D.C. line.

Somewhere near your house, probably within the block, a black box hangs on a pole. This box contains a transformer that reduces the main line voltage, usually from 11,000 volts to the 110 volts that is supplied to you and your neighbors. Farther away, at the power substation, the 11,000 volts may have been stepped down from 100,000 or even more. Many miles from the substation, at a dam or steam generating plant, the 100,000 volts has in turn been stepped up from the generator voltage of a few hundred or a few thousand.

"But why go to all this trouble?" you ask; "why step up the voltage and then step it down again? Why not build 110-volt generators, and then transmit and distribute the energy at 110 volts?"

Unfortunately, with such a procedure, electrical energy could never be transmitted more than a few miles. The loss of power in heating the transmission lines would be prohibitive. You remember that power in watts is given by the expression:

$$watts = amperes \times volts$$

But, by Ohm's Law, the voltage drop in the transmission line is given by:

$$volts = amperes \times ohms$$

Substituting this value for volts into the first equation gives:

$$power\ in\ watts = (amperes)^2 \times ohms$$

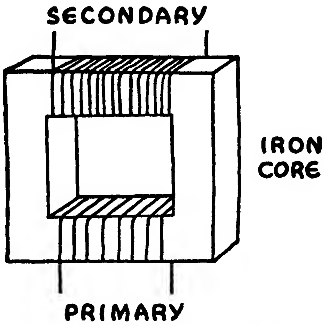
In other words, the energy consumed each second in heating the transmission line (or any resistance, for that matter) is proportional to the square of the current. Doubling the current results in four times the power loss, tripling the current results in nine times the power loss, etc. This means that in transmitting electric energy over long distances the current must be kept as small as possible—a feat that can be accomplished only by raising the voltage correspondingly.

VII. *How Are Voltages Stepped Up or Down?*

Although you have perhaps seen large power-line transformers from a distance, probably you are more familiar with those small devices that operate doorbells and toy trains by reducing the 110-volt house supply to 6 or 12 volts. All transformers operate on the same principle; and neat devices they are, too. There are no moving parts—simply two coils of wire wound on the same soft-iron core. The coil connected with the supply line is called the *primary;* the coil in which the voltage is induced is called the *secondary.* The magnitude of the voltage induced in the secondary depends on the relative number of turns of wire in the two coils. If the primary contains 10 turns and the secondary 100 turns, the voltage is stepped up approximately by a factor of 10. If the voltage is to be reduced by a toy transformer from 110 volts to 6 volts, then there must be 110/6, or about 18 times as many turns in the primary as in the secondary.

Let us see just how the transformer accomplishes its task. Alternating current flows in the primary coil and thereby induces mag-

netism in the iron core. The induced magnetic field alternates in direction, of course, with the current in the primary coil. Now most of the magnetic lines of force pass through the secondary coil, since both coils are wound on the same iron core. You remember that voltage is induced in any wire or coil that is cutting across lines of force. But the coil is not necessarily required to move. The magnetic field may move instead. Or, what is the same thing, the strength of the field may simply be increased or decreased. Hence, voltage is induced in the secondary of the transformer, as the magnetic field of the primary alternates. The greater the number of turns in the secondary, and the more rapid the changes of the field, the greater the induced voltage.



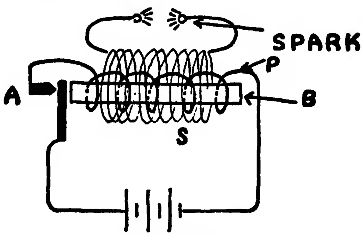
Step-up transformer. Primary coil has fewer turns of wire than the secondary.

It should be apparent that a transformer will not operate with a steady direct current. Such a current would cause no alternations in the magnetic field, and would therefore induce no voltage in the secondary coil. Generally speaking, the voltage of a direct current source can be altered only with the aid of a complicated and expensive motor-generator—a device consisting of a motor operating on the supply voltage and driving a generator that delivers a larger or smaller voltage. However, when only a small quantity of power is involved, a few volts D.C. may be stepped up to several thousand volts by means of an *induction coil,* the device that supplies high voltage for automobile ignition systems.

The induction coil is really nothing but a step-up transformer with a few turns of heavy wire on the primary and hundreds or thousands of turns on the secondary. Direct current is supplied to the primary, but the circuit is repeatedly opened and closed by a

make-and-break device. This rapid starting and stopping of current produces a changing magnetic field, and hence induces a voltage in the secondary. The induced current is alternating—flowing in one direction when the primary current is increasing and in the opposite direction when the primary current is decreasing. But the induced secondary voltage is usually greater in one direction than the other, because the magnetic field changes more rapidly on the break of the primary circuit than on the make. As a result, the secondary current is often nearly uni-directional.

Some induction coils make use of a magnetic make-and-break device similar to that in a doorbell. The famous Model T Ford coils were of this type. The more modern automobile ignition



Induction coil for stepping up D.C. voltages. (*A*) Magnetic make-and-break. (*B*) Iron core. (*P*) Primary coil. (*S*) Secondary coil. Addition of a condenser (not shown) improves the performance.

systems employ a mechanical switch operated by the rotating shaft of the distributor. When it is time for a spark to ignite the mixture of air and gasoline vapor in one of the cylinders, the primary circuit is broken; that is, the "points" of the timer are pulled apart. The resulting sudden drop in the primary current induces a momentary surge of several thousand volts in the secondary. The secondary current is then conducted through the timer to the proper spark plug, the circuit being closed through the metal frame of the automobile.

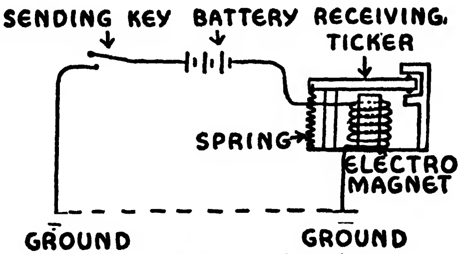
VIII. *How Do We Communicate by Electricity?*

Before leaving the subject of electricity, I should like to describe some of the simpler forms of electrical communication. We hardly realize, until we stop to think about it, the vast importance of electrical communications in our daily lives—the telegraph and telephone for our personal messages; newspapers which depend on the

teletype, telephone, telegraph, telephoto, and ocean cable for the information that they pass on to us so speedily; the radio for our entertainment and information; perhaps even television in widespread use in the near future. Most of us would feel that we had returned to the dark ages if these modern means of communicating with the whole wide world should suddenly be cut off.

We have already discussed one type of electrical communication —the doorbell. A simple type it was; but, fundamentally, all forms of electrical communication are simple. The telegraph is in many respects even simpler than the doorbell. The telegraph key, which is really nothing but a spring switch or push button, closes the circuit at the will of the operator. The receiving end, perhaps many miles away, may be connected to the sender by only a single wire, the earth forming a return path. Current is supplied by a battery or dynamo somewhere in the circuit.

When the sender closes the key, a pivoted armature in the receiving ticker is attracted to the pole of an electromagnet, just as



Essentials of the telegraph.

in the doorbell. The armature produces a click as it sharply strikes a stop. When the key is opened, a spring jerks the armature back quickly to produce a click on another stop. "Dots" and "dashes" are formed by varying the length of time the key is held closed—that is, by varying the time between clicks. As you know, the Morse Code forms letters of the alphabet by grouping dots and dashes into various combinations. To the uninitiated, the telegraph ticker appears to emit a completely scrambled series of clicks. But the expert operator learns to distinguish readily between the dots and dashes and to recognize the various combinations.

Nowadays, many telegraph receivers automatically print the letters and words on a paper tape. In the case of a teletype, the sender starts his message along the wires simply by pressing the keys

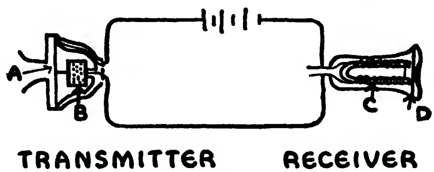
on a machine that looks and operates much like a typewriter. All these modern improvements and modifications complicate the telegraph mechanism to an extraordinary extent. Nevertheless, the principle of the old-fashioned key and ticker remains.

The telephone, too, is fundamentally a simple device. On the other hand, the switching mechanism—particularly in the case of dial phones—for connecting one subscriber with another, is overwhelmingly complex. So too, is the mechanism that enables several messages to be sent simultaneously over a single long-distance wire. You will agree about the complexity if you have ever been backstage in a large telephone exchange to view the jungle-like mazes of wire and equipment. One marvels at the intelligence and ingenuity of the engineers who build such apparatus and who must know where each of the wires goes when repairs are needed.

While there is nothing really mysterious about the individual parts of any of this telephone switching equipment, probably it would be unwise to attempt a detailed description. I wish merely to explain the operation of the telephone transmitter and receiver—devices that are, after all, the essential parts of telephone communication. Let us suppose that you have already dialed the number and are connected with your party. Just what is it that happens when you speak into the telephone transmitter? As we have already learned, the sound of your voice is transmitted through space in the form of vibrations in the air. These vibrations exert rapidly-varying pressures on a thin circular sheet of metal (called a *diaphragm*) contained in the mouthpiece of the telephone. The resulting motion of the flexible diaphragm transmits the varying pressures to a mass of carbon granules. The granules are loosely packed together in a chamber behind the diaphragm, and they have a current flowing through them. But the resistance the granules offer to the current is sharply dependent on the tightness with which the individual grains of carbon are pressed together. The greater the pressure, the better contact each granule makes with its neighbors; the lower the resistance of the whole group of granules; and, by Ohm's Law, the greater the current flowing through the transmitter. So, with the aid of the diaphragm and carbon granules, your voice vibrations eventually go out over the wires in the form of fluctuations in a current of electricity.

Now let us see what happens when this fluctuating current arrives at the receiver in the other end of the line. The telephone

receiver contains an electromagnet that attracts to its poles another thin iron diaphragm quite similar to the diaphragm in the transmitter. The receiver diaphragm is clamped tightly around its edges, but may be flexed in the center by the attractive force of the electromagnet. As the current fluctuates, the diaphragm disk is first attracted toward the electromagnet, then released. This rapid motion of the diaphragm sets up audible vibrations in the air, reproducing



Essentials of the telephone. (*A*) Transmitter diaphragm. (*B*) Carbon granules. (*C*) Electromagnet. (*D*) Receiver diaphragm.

more or less accurately the voice vibrations of the speaker at the transmitting end. I use this expression "more or less accurately" because, as you know, a telephone receiver talks in a metallic voice of rather poor quality. Much higher fidelity is attained by your radio loud-speaker in which a paper cone (rather than a metallic diaphragm) is set into vibration by electromagnets. But more later on about radio and television. First we need to look at the subject of electromagnetic radiation and some other phenomena on which these practical devices are based.

CHAPTER SEVEN

OF LIGHT AND COLOR

I. *What Is Light?*

From the days of the Ancient Greeks when Apollo drove his flaming chariot across the sun-drenched sky, down to this day of the Bright Lights of Broadway, man has always been inspired and fascinated by any grand display of light and color. And down through the ages, learned men have speculated about the nature of light. Plato talked about "divine fire" radiating from the eye and mixing with emanations from the sun and objects observed. Pythagoras attributed vision to streams of particles shooting into the eye from luminous bodies. Aristotle was less definite; but he spoke of light as a "power" or "quality" transmitted through a vague medium called the "pellucid." There was no basis for these or any of the other early theories except pure speculation.

As a result of the modern experimental approach of Galileo and others, two theories had crystallized by the beginning of the eighteenth century. One theory assumed light to be corpuscular in nature; the other assumed light to be a form of wave motion, transmitted through a strange undetected medium called the *ether*. The relative merits of these two seemingly incompatible theories were warmly debated by the scientists of that time, and the debate has not entirely subsided even to this day.

The great Sir Isaac Newton (1642–1727) threw the weight of his influence in favor of a corpuscular theory of light, not greatly different in essence from the picture of a stream of particles proposed by Pythagoras many centuries before. Newton, however, did not rule out the possibility that light might be a wave motion. Two hundred years later, at the beginning of our own twentieth century, the matter appeared to have been settled definitely once and for all. Newton's evidence had apparently been insufficient. His surmise was seemingly wrong. Subsequent experiments on interference, polarization, the velocity of light in dense media, and finally the tremendous success of Maxwell's mathematical theory of electromag-

netic radiation, had seemingly proved beyond the shadow of a doubt that light is a form of wave motion.

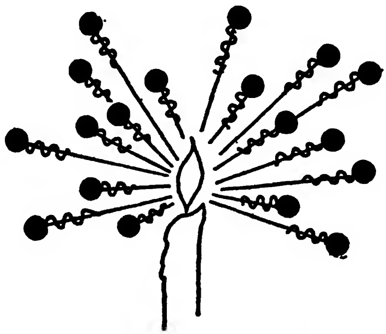
Today, we are not so sure. In fact, the simple query, "What is light?" is one of the most embarrassing of all questions for a present-day physicist to answer. Like questions about the nature of atoms and electrons, it is too completely fundamental. In the usual manner of physicists, I shall be obliged to dodge the issue partially by telling what light does and how it behaves under various circumstances, at the same time being a little vague about its actual nature.

Of course you know that, physiologically, light is something that enables us to see. Light coming from an object is focused by the lens system of the eye to form an image on a screen, called the *retina*, at the back of the eyeball. Thus the eye behaves very much like a camera in which the lens produces an image on a film or photographic plate. But what is this something that sets up nerve impulses in the retina, and affects a photographic plate chemically? Since it does these things, light must be a form of energy. Furthermore, it is something that travels nearly in straight lines (that is, it casts sharp shadows); it has a speed of about 186,000 miles per second in empty space, but travels somewhat slower in glass, water, or any other dense medium.

Sometimes light seems to have the nature of a wave motion; at other times it acts as though it consisted of little bundles of energy. We have no alternative but to adopt this concept of the dual nature of light. It seems to be a sort of Jekyll and Hyde situation. Many of the classical experimental facts discovered prior to the year 1900 require for their interpretation that light be considered a wave motion. On the other hand, a number of critical experiments performed during the past forty years require just as definitely that the corpuscular viewpoint be adopted—the supposed bundles of energy are called *photons* or *quanta*. Without giving a very definite physical picture of light, the recently developed quantum theory has attempted, in part, to reconcile the two viewpoints. As we noted earlier, the theory has been highly successful in explaining old experimental facts and in predicting new ones. Possibly you will not feel quite so disturbed about the dual nature of light, when you know that material particles, such as electrons and atoms, sometimes behave as though they were waves, or at least had definite wave properties. It would take a whole book, or perhaps several books, to describe in detail the experimental evidence for this dual person-

ality of both light rays and material particles. Needless to say, the experiments as well as the theories are often complicated. In this book, however, we shall find it sufficient to consider electrons and atoms merely as bullet-like particles; on the other hand, the wave theory of light will suffice to explain most of the radiation phenomena we shall be concerned with.

Probably you would like a more definite mental picture of the nature of a light beam. If so, you may think of myriads of little



The dual nature of light. Photons exhibit properties of both waves and particles.

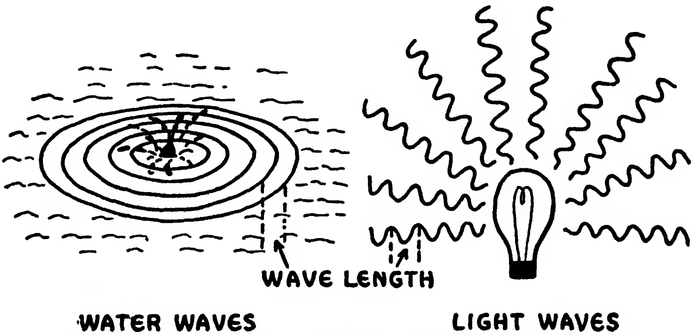
bundles of energy darting along through space. A wiggly tail should be appended to each bundle. The tail of the tadpole-like photon is supposed to represent the wave aspect of the light. Admittedly, this is a rather naive picture. However, the lack of a more precise description does not prevent us from gathering a lot of useful information about the behavior of light.

II. *On What Does the Color of Light Depend?*

By this time you may be wondering what the relation is between color and the little wiggly-tailed bundles of energy that constitute a light beam. If we consider the light to be a wave motion, then the color depends on the *wave length;* that is, on the distance from the crest of one wave to the crest of the next. In order to visualize the concept of wave length, think of the analogy of water waves formed by dropping a stone into a calm pond. The wavelets travel outward in circles that grow continuously larger, the wave length being the distance between the crests of successive waves. The water waves, it is true, travel only on the surface (that is, they are two-dimensional); while light waves, like sound waves, radiate in all directions

through space. Nevertheless, the idea of wave length is the same in the two cases. Red light has the longest wave length, yellow the next shorter, and so on down the spectrum through green, blue, and finally violet. Incidentally, the wave length of red light is only about three one-hundred-thousandths of an inch.

There are other ways of looking at the matter of color. By analogy with sound, red light has the lowest pitch or frequency of vibration and violet light has the highest pitch. You see that there is an inverse relation between frequency and wave length: waves with the lowest frequency have the longest wave length, and *vice versa*. If, instead of the waves, we talk about the little bundles of

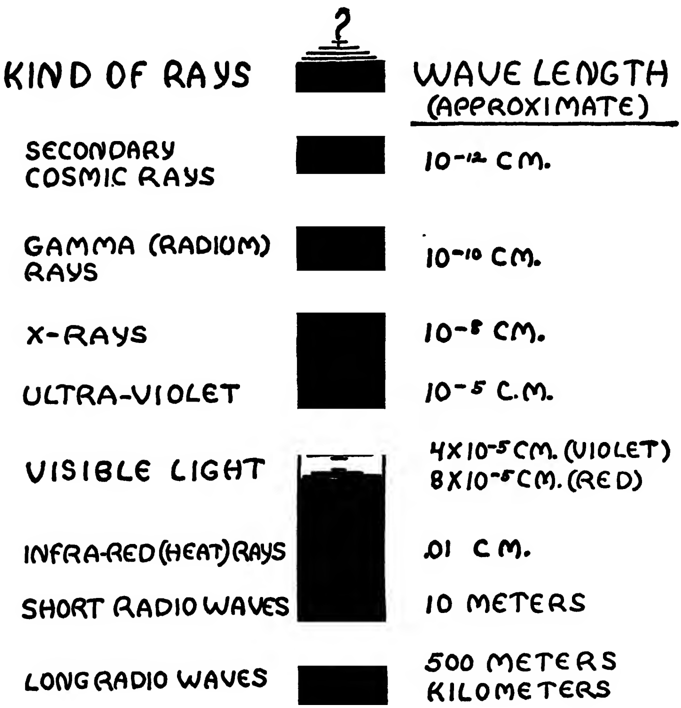


Wave length: the distance between crests of successive waves.

energy, those bundles that contain the most energy are violet, while red bundles contain the least energy. We might note here that the visible spectrum constitutes only a tiny portion of the whole range of electromagnetic waves which are similar in nature to light, but which are invisible. Ultra-violet light is of shorter wave length than violet, x-rays are still shorter, and gamma rays from radium and other disintegrating atomic nuclei are even shorter yet. On the long wave length side there are infra-red and heat rays, and finally radio waves which may have wave lengths of more than a mile.

Now that we know something about the nature of light and color, let us look around and explain some of the things that we see. A colored transparent object, such as a piece of red glass, transmits red light, but absorbs all or most of the other colors that shine on it. But what about opaque (non-transparent) objects? Why is one piece of cloth, for example, red, while another is blue? The answer

is that we see only the light that is reflected from such an object.* White light, which contains all colors, shines on our piece of cloth. The dye in the cloth is of such a nature that it pretty well absorbs



The electromagnetic spectrum. Visible light constitutes only a tiny portion of the whole known range.

all colors except red. The red is then reflected, and that is what we see. If some other color or combination of colors is reflected, then

* From a technical viewpoint, the term *reflected* is used here in a rather loose sense. In the case of pigments and dyes, the light actually penetrates a short distance under the surface, and is then reflected from the lower layers. Hence, the color phenomena are due really to *selective absorption* (as in colored glass), and not to reflection. On the other hand, the colors of metals and solid dyes with metallic luster result from true selective reflection at the surface.

we may get any hue or tint. Incidentally, this gives us a hint why many fabrics look to have one color under artificial light, and another color in daylight. The artificial light is of a different composition from daylight, and therefore the amount of each color reflected is different.

Light from an incandescent lamp, for example, contains proportionately more red and yellow than does sunlight, and hence emphasizes the red and yellow hues, weakening the blues and violets by contrast. Strangely enough, though, yellow may appear quite white under an incandescent lamp. This comes about because our eyes, being accustomed to the yellowish light from the lamp, no longer distinguish the lamplight from the real white of sunlight. Hence, a piece of yellow cloth or paper, reflecting all the colors contained in the lamplight, appears to be white.

In extreme cases where artificial light contains only one color, or a great preponderance of one color, weird effects are sometimes obtained. Thus, a pure red necktie will appear completely black when viewed under a blue mercury lamp. That is, all the light will be absorbed and none reflected. However, the blue mercury light does contain some yellow, as can be demonstrated with the aid of a prism or other spectroscopic equipment that breaks the light up into its component colors. If your red necktie partially reflects yellow in addition to red (as many red dyes do), then the tie will appear not black, but yellow, when viewed in the blue light of the mercury lamp. Your blue automobile, on the other hand, will appear black under one of the newly-developed bright yellow sodium street lamps. The blue paint reflects little or no yellow light, except from the outermost glossy surface.

You might like to try for yourself some simple experiments of the type just described. Colored objects viewed under almost any colored light will give interesting effects. But there is one thing to look out for: in any dim light the eye does not respond in a satisfactory manner to color. At dusk, for instance, all objects appear grayish, and it is difficult to distinguish one color from another. So unless you pick a well-lighted spot, your car or other object that you are looking at may appear dark, not because of the color of the illumination, but simply because there is insufficient light.

If you have ever done any painting, you are probably aware that yellow and blue pigments, when mixed, give green. But would it surprise you to know that a beam of yellow *light* mixed with a beam

of blue *light* appears *white* when projected on a screen? Blue and yellow are *complementary colors*—as are red and green. When any two complementary colored lights are mixed, the combination appears white to the eye, just as does a mixture of all colors in sunlight. This is a physiological matter. Our eyes and minds simply respond in this fashion. On the other hand, the green resulting from mixing blue and yellow pigments is a physical matter. Blue pigment reflects some green light in addition to the blue. It absorbs all other colors. Yellow pigment, too, reflects some green besides the yellow. When the two pigments are mixed, only green is reflected by the combination. One or the other of the pigments pretty completely absorbs all other colors.

Similar arguments apply to mixtures of all kinds of dyes and pigments. Sometimes, however, the final appearance to the eye is unexpected and the explanation is complicated. Browns and purples, in particular, usually consist of combinations of many colors.

The camouflage expert has to be well acquainted with the principles of color mixing and color analysis. For example, the green paint he puts on a factory roof may look exactly like lawn grass when viewed in normal daylight, but this is not enough. It must also have the same hue and brightness as the surrounding lawn when viewed by other kinds of light—the observer in the enemy plane above will certainly not hesitate to look through various colored filters if he has reason to suspect that things are not just as they seem below. Even when the camouflage job is entirely satisfactory for all visible light, it is sometimes detectable when photographed through an infra-red filter.

III. *Where Does Light Come From?*

We have learned already that most cold bodies can be seen only because of the light reflected from them. This is the case, of course, for the great majority of the objects we look at. These things are invisible in the dark. Even some of the heavenly bodies—the moon and the planets—appear bright to us only because sunlight is reflected from them. At full moon we see the whole of the surface that faces the earth. At other times, depending on the relative positions of the sun, moon, and earth, we are permitted to view only a portion of the moon's surface from which sunlight is reflected. Incidentally, aside from small oscillations, the moon always keeps its same face turned toward us. No one has ever seen the far side.

The planet Mars is reddish in color for the same reason that a red piece of cloth is red: its surface is a material that reflects red light and absorbs the other colors, at least partially. The planet Venus has a green tinge because of the predominant reflection of the color green.

The other heavenly bodies—stars, comets, and meteors—are self-luminous like our sun. If any of the stars have cold planets circling around them, these satellites are too far away to be visible even with the most powerful telescopes. The cause of luminosity in the case of comets is not definitely known. Meteors, or "shooting stars," are generally tiny fragments of solid rock-like material, often no larger than a pea. Friction heats them to a brilliant incandescence when they plunge through the resisting atmosphere of the earth. Only the very largest meteors succeed in reaching the ground without burning up and vaporizing. The stars and our sun are luminous because of their high temperatures. How they became hot in the first place, and how they maintain their temperatures, are riddles that only now are being solved. Almost certainly, much of the solar energy comes from the transformation of hydrogen into helium, through a complicated series of atomic transmutations. Thus, the scientists' dream of atomic energy is actually realized on the sun and the other stars.

There are exceptions to the rule that cold bodies are visible only by light reflected from them. Glowworms, fireflies, the so-called radium dials on watches and clocks, and all sorts of fluorescent materials emit what is often termed "cold light," or *luminescence*. The cause of luminescence, especially in the case of the living organisms, is something of a mystery. It is often associated with chemical reactions—oxidation in particular. We shall have something to say about the uses of fluorescent materials a little later.

In any case, if an object is to emit light of its own accord, its atoms and molecules must be violently stirred up. As we know, heat is effective for the purpose. Any solid or liquid body begins to glow with a dull red heat when its temperature is raised to about 1000 degrees Fahrenheit. As it gets hotter, the light appears yellow, then white, and finally bluish. A wide continuous range of wave lengths is always emitted; but the color of greatest intensity shifts from the red toward the shorter wave length blue as the temperature is raised.

The astronomers tell us that the surface temperature of some of the very hot "blue" stars is over 35,000° F. Our sun is reasonably

hot as stars go, with a surface temperature of about 10,000° F. It is interesting to note that the wave length of maximum intensity (of greenish-yellow color) in sunlight is almost exactly the wave length to which our eyes are most sensitive. The process of evolution has apparently adjusted us automatically to our environment.

Here on earth, the carbon arc is nearly as hot as the outer surface of the sun. Other man-made incandescent sources of light operate at lower temperatures. The light emitted by a gas or oil lamp is due largely to the presence of hot bits of unburned soot in the flame; the color is yellow, because the temperature is comparatively low. Incandescent electric lights are limited by evaporation of the tungsten filament to an operating temperature of abut 5000° F.—half the temperature of our sun's surface. It is desirable that the lamps run as hot as possible in order that a large fraction of the energy be radiated as visible light and less as long wave length invisible heat (infra-red) rays. Of course, the oxygen of the air must be pumped out of the bulbs, or the filaments would burn up almost instantly. For this reason, all lamps made some years ago were highly evacuated. The smaller-sized lamps still are. But in a vacuum, the tungsten filament evaporates rather quickly. In order to slow down the evaporation rate, and thus to permit a higher operating temperature, an inert gas (usually a mixture of argon and nitrogen) is nowadays introduced into the larger-sized bulbs. The atmosphere of inert gas helps to keep the evaporated tungsten atoms in the vicinity of the filament, and many of them return and condense on the filament instead of being deposited on the walls of the bulb. The efficiency of the lamp is further increased by winding the fine filament wire into a helix or spring-shaped spiral; and in the most recent lamps, this spiral is itself rewound into a larger helix.

Despite all these modern refinements in manufacture, most of the electrical energy is still wasted in heat, even in the most efficient incandescent lamps. As we saw in the last chapter, less than 15 per cent of the energy is radiated as visible light. But to make matters worse, most of this 15 per cent lies in the red and blue portions of the spectrum where the eye is relatively insensitive. If all the light emitted by the lamp were of a greenish-yellow color (that is, the color to which our eyes are most sensitive), then we should obtain the same illumination as we do now if only 2 or 3 per cent of the electrical energy were converted into light. In other words, the visual efficiency is really only 2 or 3 per cent. It would be highly advantageous, then, from an efficiency standpoint, to devise a source

of light capable of emitting a very large portion of its radiation in the green or yellow. Such a result is attained in the yellow sodium lamps and, to a lesser extent, in the blue mercury lamps. The sodium lamps have an efficiency of nearly 10 per cent, and the mercury lamps as high as 7 per cent. These values are to be compared with the 2 or 3 per cent of the incandescent bulbs.

Back in Chapter Five we learned how an electric current is conducted through these gas-discharge lamps. But where does the light come from? We have seen already that in every case of light emission, the atoms of the emitting material are violently stirred up. Electrons, smashing their way through a solid metal filament, heat the filament to incandescence. In much the same way, the electrons set the atoms of a gas into violent agitation. But the gas atoms are free to move about and act independently, not being tied down to a more or less definite position as are the atoms of a solid body. The final result is therefore different. While light of all colors (that is, a *continuous spectrum*) is emitted by a hot solid body, only specific wave lengths, characteristic of the gas, are emitted by the agitated gas atoms. What happens is this: the rapidly moving free electrons, which constitute the major part of the current, smash into the neutral gas atoms; sometimes, as we have seen, they ionize the atoms, but more frequently they merely knock the electrons out of their normal positions without completely removing them from their parent atoms. The atoms containing such disturbed electrons have had energy added to them and are said to be in an *excited state*. After a very short interval of time, the excited atoms lose their excess energy, and the disturbed electrons return to their original positions. Each time such a return occurs, one of the wiggly-tailed photons, or bundles of light energy, is emitted. Strangely enough, the energy changes are limited in any given kind of atom to a comparatively few discrete values. In other words, although millions of atoms are radiating light almost simultaneously, they emit only a limited variety of wave lengths or colors. These wave lengths are characteristic of the gas.

In the neon lights, most of the emitted wave lengths are in the red portion of the spectrum;* while in a sodium lamp the characteristic color is yellow. The blue mercury lamps emit rather intense

* Other colors—blue, green, etc.—are obtained in the advertising signs by using various other gases, such as mercury vapor and argon, in place of neon. Sometimes, the glass tubes that contain the discharge are colored; that is, the glass absorbs the unwanted colors, transmitting a preponderance of the desired color.

violet, green, and yellow colors as well as blue; but the combination appears blue to the eye.

Each chemical element emits colored spectra of wave lengths different from the wave lengths of all other elements. It follows that any element may be uniquely identified by measuring the wave lengths contained in its spectrum. With the aid of a prism or other spectroscopic equipment, the light emitted by any vaporized material may be broken up into its component colors; and the chemical elements present are then revealed by their characteristic spectral lines. This method of analysis is frequently employed in chemical laboratories, especially to detect impurities in materials when the quantity of impurity is so small that ordinary chemical methods would be difficult. By similar means, astronomers have discovered that the sun and stars contain the same chemical elements that we have on earth. The valuable balloon-lifting gas, helium, was discovered by its spectrum in the corona of the sun before its presence on earth was suspected.

IV. *What Causes the Color of the Sky?*

Let us turn now to a discussion of some natural color phenomena, particularly those to be observed in the sky. Most people who live far enough north have been privileged to gaze with wonder and awe at the magnificent colored displays of the *aurora borealis,* commonly called the northern lights.* The aurora has been seen in many shapes and colors; but, in principle, its light is believed to originate in much the same way as the light from a neon sign or sodium lamp. High-speed free electrons, shot out from the sun, plough through the rarefied oxygen and nitrogen in the upper atmosphere, and cause the emission of light. The aurora is not visible near the equator because the electrons that produce it are picked up by the earth's magnetic field and are deflected in a spiral path toward the poles of the earth. These facts about the aurora seem to be pretty well established, but many of its details are as yet unexplained.

Though not all of us have an opportunity to view the striking auroral effects in the night sky, everyone does have the privilege of viewing the equally beautiful blue of the midday sky, as well as the gorgeous reds and yellows that frequently accompany the rising and the setting of the sun. Have you ever stopped to wonder why the sky is blue? It is not a matter to be taken for granted. In fact, if

* In the southern hemisphere, similar displays are termed *aurora australis.*

you went up in a stratosphere balloon to a height of about ten miles above the earth's surface, you would find that the sky was blue only in the direction of the horizon. Overhead it would be nearly black, and the stars would be visible.

You might guess that the earth's atmosphere has something to do with the blue of the sky. And so it has. It deflects or, more precisely, *scatters* the sun's rays in all directions. But, since sunlight is white, something must have happened to the red portion of the light, thus leaving a preponderance of blue. As a matter of fact, the long wave length red rays tend to go straight through the atmosphere; while the short wave length blue rays are scattered from their original direction by the air, water, and dust particles that are overhead. This scattered light is what we see when we look up into the sky. Ten miles up in a stratosphere balloon, there is so little air left overhead that practically no light is scattered downward; hence the observer looks out into the empty black void of space.

When the sun is low, as at sunrise or sunset, the sky near the horizon is likely to appear red or yellow, because we see the light that has come to us a long distance through the atmosphere. Most of the short wave length blue and green has been scattered out and lost. The degree of redness on any particular occasion depends on the number and character of the scattering particles in the path of the light. Minute water droplets and dust particles are especially effective in scattering out the shorter wave lengths.

This brings up the matter of penetrating rays and, incidentally, explains why it is desirable to use red or yellow light to penetrate fog, smoke, or haze. Thus, red neon lights are very effective as aeroplane beacons in thick weather. On the other hand, merely covering up a white light with red or yellow glass does not greatly help matters. Such a procedure cuts out the blue and green without adding anything to the penetrating red portion of the spectrum. In this respect, people who sell fog-penetrating spot lights for automobiles sometimes make absurd claims for their products. The concentrated and powerful beams of light thrown out by these devices may penetrate fog rather effectively, but the amber-colored lenses only cut down the intensity and add nothing to the penetrating rays. There may be, however, some slight advantage in removing the short wave length radiations, since these would be scattered preferentially backward into the driver's eyes, and might increase the glare of the fog.

The invisible infra-red rays are even better than red and yellow for penetrating haze. Probably you have seen pictures of landscapes

taken with photographic plates specially sensitized for the infra-red. In hazy weather, distant objects completely invisible to the eye stand out clearly in these infra-red pictures. Infra-red photography is extremely valuable in mapping by aeroplane, especially in wartime, when the pilot is frequently able to take pictures of the earth through the haze, while his plane remains invisible to the enemy below.

The smoke screen expert, like his peacetime counterpart the sky-writer, has just the reverse problem. His task is to fill the air up with a cloud of particles that will scatter light very effectively, so that the rays of sunlight reflected from a battleship (for instance) cannot proceed in straight lines to the observers on enemy ships in the distance. Scattering, and not absorption of the light, explains the action of smoke screens. The substance from which the smoke is made may be, and usually is, quite transparent. The *size* of the particles determines the effectiveness of the scattering. A given quantity of material scatters light best when it is broken up and dispersed as particles approximately one wave length of light (about two one-hundred-thousandths of an inch) in diameter. What stuff to use, and how to go about breaking it up and dispersing it in the air, are technical questions of some difficulty, but the most desirable size of the particles is known in advance.

V. *What Are the Properties of Ultra-Violet Radiation?*

In contrast with the infra-red, the invisible ultra-violet light on the short wave length end of the spectrum penetrates the atmosphere even more feebly than does blue or violet. In fact, the ultra-violet is not only scattered readily but, below a certain wave length, it is absorbed by the atmosphere, just as the visible blue and violet are absorbed by a piece of red glass. Incidentally, the very short wave length ultra-violet is effective in ionizing the air. Radiation of this sort coming from the sun is at least partially responsible for the ionized layers that lie between 50 and 150 miles above the surface of the earth and have such profound effect on radio transmission. The *Kennelly-Heaviside layer* (so named after the men who first proposed its existence) accounts for "fading," "skip-distance," and similar annoying phenomena. But the Kennelly-Heaviside layer also has its value. It makes possible short-wave transmission over great distances. The radio waves would escape into space and could be sent only a few miles along the surface of the earth if they were not in effect curved around the earth by reflection at the ionized layers.

At night and in winter the layers change their character; and this alteration generally results in improvement of radio reception.

Since life on our earth has evolved under a protective blanket of air, it would doubtless prove disastrous to human beings as well as to most plants and animals if all the ultra-violet radiation from the sun were suddenly allowed to penetrate to the ground. Artificially generated ultra-violet, in small doses, is used in hospital operating rooms and other places for the purpose of killing germs in the air. As you know, the ultra-violet that does get through the atmosphere is effective in producing sunburn. At high altitudes, where there is less air for the sunlight to penetrate, the burning of the skin takes place more rapidly and is more severe than at sea level. Many mountain climbers have learned this fact to their sorrow.

Many transparent materials, such as ordinary window glass, partially absorb even the portion of the ultra-violet radiation that penetrates through the air. You cannot get a burn from sunlight that has come through a closed window. Likewise, you receive no appreciable quantity of ultra-violet from an ordinary incandescent lamp. The small quantity of ultra-violet emitted by the filament is nearly all absorbed in the glass bulb. On the other hand, carbon arcs which operate in the open air emit strong ultra-violet radiation and are often used in sun lamps. The radiation from a welding arc contains enough ultra-violet to be dangerous to the welder's eyes, if he were not protected by his mask. Pure quartz, though much more expensive than glass, does transmit ultra-violet radiation. Therefore, the mercury arc, which emits very intense ultra-violet, may be employed as a sun lamp if the discharge is enclosed in a quartz tube instead of a glass tube. Such lamps must be used with caution, and the eyes must always be protected.

Quartz mercury lamps are now being manufactured in a compact and convenient form and are very effective as sources of ultraviolet for fluorescent displays. Certain minerals, and synthetic compounds made especially for the purpose, have the property of absorbing the invisible ultra-violet radiation and re-emitting part of the energy as strikingly colorful visible light. This phenomenon is known as *fluorescence.** When the fluorescent substances are incorporated into paint and used on signs for advertising purposes, or are

* Fluorescent light may be produced also by bombardment of certain materials, such as zinc sulfide, with high speed electrons. Television screens operate on this principle.

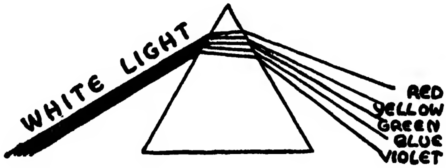
applied to chorus girls' costumes on the stage, very beautiful colored effects result. The painted objects appear to be one color when illuminated by visible light, but glow brilliantly with an entirely different color when they are irradiated in the dark with invisible ultra-violet rays.

Because of their high efficiency and consequent low cost of operation, the new fluorescent lamps now on the market are becoming very popular for lighting stores and large buildings. The long glass tubes contain a mercury vapor discharge, and are coated with fluorescent materials on the inside. The mercury arc itself gives a rather unpleasant ghostly blue light, but it also produces large quantities of invisible ultra-violet radiation. These invisible radiations are absorbed by the fluorescent wall coating and are converted into visible light. By properly combining various materials in the fluorescent coating, light of almost any color, including white, can be obtained. The efficiency is high, since the invisible ultra-violet, which would ordinarily be wasted by absorption in the glass, is salvaged by the fluorescent layer and turned into useful light.

VI. *What Causes a Rainbow?*

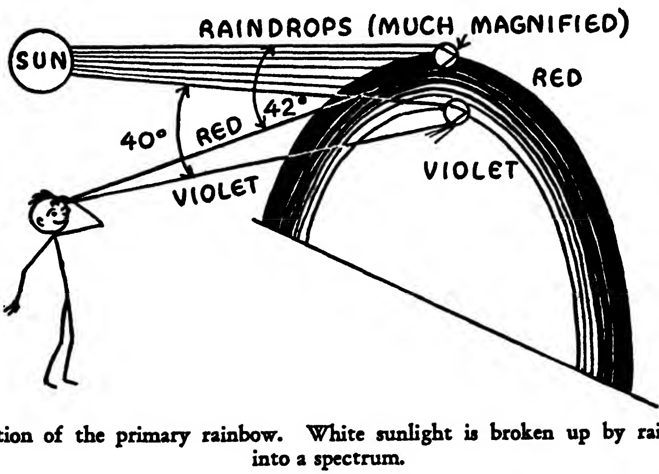
Returning once again to natural color phenomena: can you explain the formation of the rainbow? Probably you have at least a vague idea that a rainbow is due to an interaction between sunlight and raindrops. But let us try to get a more definite picture. Consider first the conditions that are required for a rainbow to be visible. If you are on level ground, the sun must be near the horizon and not overhead. You do not see a rainbow at noon—except possibly in winter when the sun is low. In addition, the sunlight must be shining on raindrops that are located on the opposite side of you from the sun. If these requirements are fulfilled, you should see a rainbow when you look away from the sun. Sunlight entering a rain droplet is broken up into its component colors, just as if it had passed through a glass prism. Part of this colored light inside the droplet is reflected back from the far side; and if you happen to be located at just the right position relative to the drop, you will see a single color—red, for example. The other colors of shorter wave length are reflected to your eye with sufficient intensity to be visible (that is, are effectively focused) only from drops lower down in the sky than those which reflect the red. In other words, red appears on the outside, violet on the inside of the bow.

The geometrical requirements for reflection and focusing of the light within the rain droplets make it impossible for a person standing on level ground to see more than a part of the circular rainbow. The higher the sun above the horizon, the smaller the visible arc. But if you wait long enough at the summit of a mountain, you may



A prism breaks up a beam of light into a spectrum of the component colors.

sometime be rewarded with a view of the whole rainbow circle, or nearly the whole circle. Aeroplane passengers sometimes do have the opportunity of seeing the entire circle spread out on a cloud beneath them, with the shadow of the aeroplane from the overhead sun falling in the center of the circle.



Formation of the primary rainbow. White sunlight is broken up by raindrops into a spectrum.

Sometimes a fainter secondary rainbow can be seen outside the primary bow. This is due to multiple reflections inside the droplets; and the order of the colors is reversed—red on the inside, violet on the outside.

Artificial rainbows, similar to the natural ones but on a miniature scale, may be formed in any fine spray of water, provided the sun is

low and the observer is standing between the sun and the water droplets. The exquisite array of pastel shades characteristic of the rainbow often appears in the mist of a waterfall, or even in the spray from your garden hose.

Moonlight rainbows have been seen occasionally. The optical conditions are the same as for a solar rainbow, but the moon must be very bright.

VII. *What Is the Cause of Color in Thin Transparent Films?*

Everyone has observed the brilliant colors often visible when light is reflected from thin films such as from oil spread on water. Soap bubble films give similar effects. The colors are not caused by selective reflection or absorption, as with other colored objects. The thin films are transparent. They absorb practically no light. Nor is the effect one of *dispersion;* that is, a breaking-up of the light into its component spectral colors as in a prism or raindrop. What, then, is the cause of the color?

A new phenomenon, known as *interference,* enters the picture here, and the wave theory of light gives us a simple explanation. If the film has just the right thickness, waves reflected to our eye from the front surface combine with those reflected from the back surface in such a fashion that both waves are destroyed. In order that this may happen, the crest of one of the waves must meet the trough of the other; then they will cancel each other and the final result is no wave at all. Now for a given thickness of film, this destructive interference can occur for only a single wave length or color. Consequently, that color is missing from the white light reflected from the film; and if the missing color happens, for example, to be red, then the remaining light has a blue or green appearance. Likewise, if blue is missing because of interference, then the rest of the light appears red or yellow to the eye. If green or yellow is missing, the result is a combination of violet, blue, and red, which is usually some sort of purple.

Thin-film interference accounts for the color of many objects. The delicate tints in the mother-of-pearl layers of certain sea shells are at least partially the result of this interference. The array of colors on a piece of steel tempered differently in various portions, is due to a thin film of iron oxide that varies in thickness over the surface. Likewise, if you have ever heated a shiny sheet of copper in a flame, you have probably noticed the bright colors playing over the

surface as the thickness of the copper oxide film changed rapidly. Whenever light is reflected from very thin transparent films or layers, it is safe to assume that at least part of the color effect is due to interference. Incidentally, if a film of this sort is illuminated by light of a single color (for example, yellow from a sodium lamp), the film appears either light or dark, depending on its thickness, but never with a hue different from that of the illuminating source. The film cannot manufacture a color that is not already present in the light.

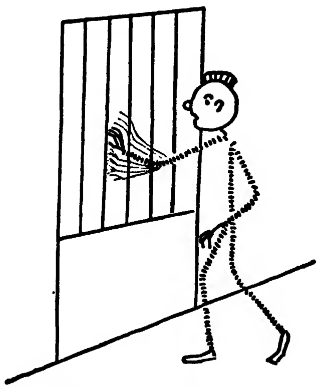
VIII. *What Is Polaroid?*

Before leaving this chapter I should like to introduce you to a phenomenon that, until the last few years, was scarcely known outside of the laboratory—though it has long been of theoretical importance. A recent clever invention, however, seems likely to bring this laboratory curiosity into widespread practical use. The phenomenon in question is the *polarization* of light.

In order to understand what is meant by the polarization of a wave, imagine yourself in prison—just for a moment. Suppose you see a friend passing by, outside the prison, and you wish to wave to him through the barred window of your cell. The bars are vertical. You become excited and rush to the window, waving your arm in all directions—horizontally, vertically, and at various other angles. But your hand always moves at right angles to the direction in which you yourself are approaching the window. Your hand executes a sort of wave motion, similar to that in an unpolarized beam of light. Now you arrive at the window and try to insert your hand between the bars, at the same time continuing to wave. The bars prevent you from moving your hand horizontally. You can move it only up and down in a vertical direction. In other words, the wave motion of your hand is *polarized* in the vertical direction. If the bars had been oriented in some other way—horizontally, for example—then the wave would still have been polarized, but in the new direction.

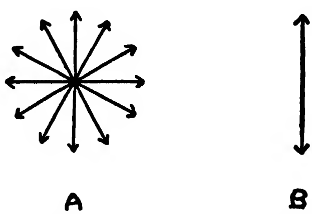
Now you may be allowed out of jail to consider a beam of light. Ordinary light, coming from the sun or almost any other source, is unpolarized. Its vibrations lie in all directions in the plane perpendicular to the direction in which the light itself is traveling. The wave length is so small that ordinary bars will not serve to polarize the light. However, the rows of atoms lined up uniformly in cer-

tain crystals serve the purpose very well. All vibrations in the horizontal direction, say, are absorbed; those in the vertical direction are allowed to get through. In other words, the beam of light is polarized by passage through the crystalline material.



The bars "polarize" the wave motion of the prisoner's arm.

There are several ways to obtain polarized light. Reflection at the proper angle from a water or glass surface is one method. Crystals such as tourmaline, Iceland Spar, and quartz are effective polarizers when cut and arranged properly. But all of these older polarizing devices are either clumsy, or absorb too much light, or are limited to light beams of small area. The invention of a new material, *Polaroid,* has removed the previous limitations. Polaroid



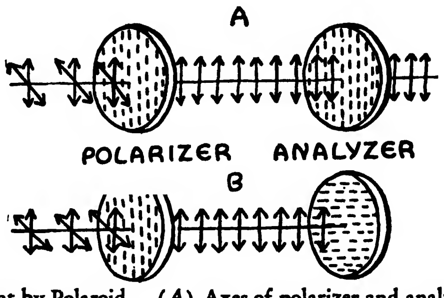
(*A*) Unpolarized light (coming out of the page toward you) vibrates in all planes. (*B*) Polarized light vibrates in only one plane.

comes in a thin sheet (usually sandwiched between two glass plates for protection) and looks much like Cellophane. It is in fact a material similar to Cellophane; but imbedded in it are many tiny crystals (of quinine-iodide sulfate) all oriented in the same direction.

This orientation is achieved by stretching the sheet of Polaroid during the process of manufacture, while the material is still in a plastic state. Nearly all light vibrating in one direction is transmitted by the Polaroid sheet; nearly all vibrating in the other direction (at right angles to the first) is absorbed.

Now, your eye cannot distinguish between polarized light and unpolarized light. You might wonder, then, how it is possible to detect polarization at all. But the problem offers no great difficulty. Suppose a second sheet of Polaroid (called the *analyzer*) is placed back of the first one. The light beam polarized by the first sheet will pass right on through the analyzer unimpeded if the sheets are so oriented that the crystals are lined up in the same direction in both. But now suppose that the analyzer is rotated through a right angle about an axis parallel to the light beam. Then the crystals in the analyzer no longer transmit the polarized light, but absorb it instead. It is as though the window of your prison cell were fitted with a second set of bars, crossed with respect to the first set.

Hence, simply by rotating one sheet of Polaroid with respect to another fixed sheet, a beam of polarized light can be transmitted or



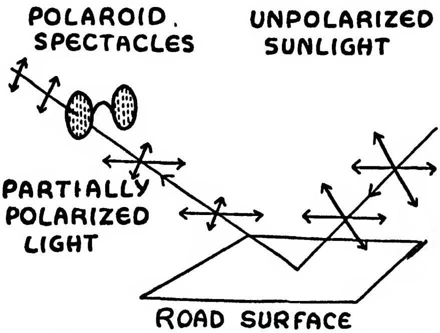
Polarization of light by Polaroid. (*A*) Axes of polarizer and analyzer parallel: light is transmitted by analyzer. (*B*) Axes of polarizer and analyzer crossed: no light is transmitted by the combination.

extinguished at will. Each half revolution the light is extinguished. In between, it is transmitted. The effect is indeed striking when one looks at a source of light (such as an incandescent lamp) through a pair of transparent Polaroid films, and sees the bright light blotted out completely when the films are turned to the "crossed" position.

By now you probably wonder what possible practical applications could be found for this rather odd phenomenon that we call polarization. Engineers have made use of it for many years in

analyzing the strains set up in celluloid models of build... and other structures. Celluloid possesses polarizing qualities only when it is deformed as a result of applied forces. Hence, a celluloid model of an engineering structure may be used to find out whether excessive strain will occur in the joints and other portions of the finished framework. With the proper polarizing equipment, colored lines or bands of light become visible at the regions of strain in the celluloid model.

Polaroid promises to widen the application of polarized light to several everyday uses. Polaroid goggles for motorists are now on the market. These are effective in reducing glare, because sunlight is partially polarized in the process of reflection from roads and other



Polaroid goggles reduce glare by eliminating the polarized portion of the light reflected from roads and other surfaces.

surfaces. Hence, by properly orienting the Polaroid inserted in the goggle lenses, the glare may be cut down without reducing seriously the brightness of most objects. Other glare-reducing Polaroid devices, such as reading lamps and photographic filters, are also available.

Polaroid could be of great value in night driving by eliminating the glare from the headlights of passing automobiles. Polaroid sheets would be inserted in the headlight lenses and in the windshields of all cars, and would be oriented to polarize the light at an angle of 45° with the vertical. The visibility of the road (illuminated by your own headlights) would not be seriously impaired; but the light from a car coming toward you would be absorbed in your windshield. Up to the present, Polaroid in large sheets has been too costly for application in this fashion. Also, there are some technical diffi-

culties to be mastered. But the time may come when all automobiles will be equipped with Polaroid in the windshields and headlight lenses, just as they are now equipped with safety glass.

At least one other application of Polaroid appears promising. Motion picture technicians have always wished that they might increase the realism of the projected pictures by the illusion of three-dimensional effects. Such stereoscopic movies are now feasible, provided the members of the audience are willing to wear Polaroid spectacles during the performance. Just how this would work, we shall see in the next chapter when we discuss the old-fashioned stereoscope—an optical device that graced the parlors of all good homes fifty years ago. If you went to the New York World's Fair a few years ago, perhaps you saw such three-dimensional movies, and wore a pair of the Polaroid spectacles—this movie was a feature of one of the most popular exhibits there.

CHAPTER EIGHT

VISION AND THE BENDING OF LIGHT RAYS

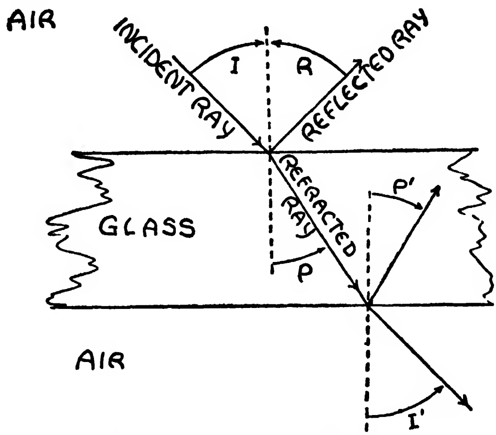
I. *How May Light Rays Be Bent?*

Sir Isaac Newton favored the corpuscle or particle theory of light rather than the wave theory, chiefly because he could discover no evidence that light has any tendency to bend around corners while it is traveling in a homogeneous medium. Ocean waves curve around back of a breakwater or other obstacle. Sound waves may be heard on the opposite side of an intervening hill or building. If light is a wave motion, why should it, of all wave motions, cast sharp shadows?

The answer is that the experimental technique of Newton's time was not good enough to detect the bending. Actually, light does bend around corners just a tiny bit; but its wave length is so short that the bending can be discovered only by carefully performed experiments. Would it surprise you to know that the shadow cast by a very small round object not only shades off at the edges, but actually has a light spot at the center? If light did not bend around corners, the shadow would be equally dark at all points. Furthermore, long wave length electromagnetic radiations—radio waves—bend around mountains or other obstacles readily enough. This kind of deviation is known as *diffraction;* and the wave theory accounts for it completely. Without complicated modifications, the corpuscular theory does not.

I have mentioned the phenomenon of diffraction only in passing, because I wished to make my story of the bending of light rays complete. For most practical purposes we may neglect diffraction effects. Henceforth it will be sufficient for us to assume that light is propagated in straight lines—unless it meets a new medium (glass or water, for example) in its travels. When it does arrive at the boundary of a new material, the light beam is partly reflected, and it is partly refracted. Each of these phenomena (*reflection* and *refraction*) normally results in a sharp change of direction at the point where the beam encounters its new environment. This is the kind of bending that we are going to discuss in the ensuing pages.

First, it will be necessary for you to know something about the laws governing reflection and refraction. In very simple language we can say that when a beam of light strikes a water suface at an angle, part of the light bounces off like a ball (that is, part is re-



Illustrating the laws of reflection and refraction. Behavior of a light ray in passing through a sheet of glass (or other dense medium). Angles *I*, *R*, and *I′* are all equal; angle *P* equals angle *P′*.

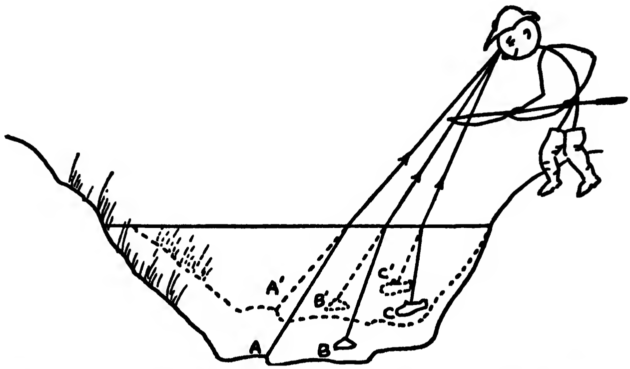
flected), and part enters the water. In the case of the reflected ray, the angle of incidence equals the angle of reflection. The transmitted (refracted) portion of the beam is bent sharply downward, and its speed is reduced as it enters the denser medium, water. The greater the optical density of a medium* like water or glass, the greater the bending when a light ray enters or leaves the material.

One common example of refraction is the "wavy" or distorted appearance of objects viewed through ordinary window glass. The glass surfaces are not perfectly flat, and the light rays are bent in varying degrees as they pass through different portions of the glass. Plate glass does not distort the view because its surfaces are much smoother.

No doubt you are aware that a pond of water looks shallower than it actually is. Also, a straight stick or rod appears to be bent at the point of immersion when it is placed obliquely into a vessel of

* The optical density is measured by a quantity called the *index of refraction*, equal to the ratio of the speed of light in a vacuum to the speed in the dense medium. Hence the index of refraction is equal numerically to unity for a vacuum, and is greater than unity for any other medium. For water it is 1.33; for glass, about 1.5 to 1.6.

water. These effects are both due to refraction. Light rays coming from the bottom of the pool or from the immersed stick are bent as they leave the water. Your eye, however, has no way of knowing what has actually happened. So far as the eye can tell, the rays have come straight from their source. The source simply appears to be in one place, whereas it is actually somewhere else. One might think of the matter as a sort of elementary optical illusion.



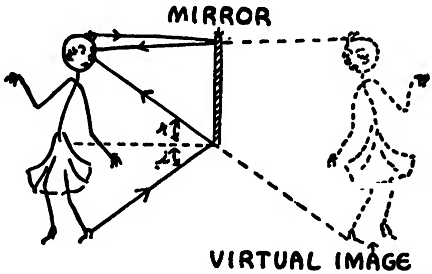
A pool of water appears shallower than it actually is, due to the refraction of light rays. Rays coming from objects at *A, B,* and *C* appear to originate at *A′*, *B′*, and *C′*.

II. *How Does a Mirror Form an Image?*

In the same way that the appearance of the bottom of a pool is an optical illusion, one could say that every image formed by a plane mirror is also an optical illusion. When you look into a mirror, you see yourself apparently behind the mirror, whereas you are actually in front. Because the light rays never pass through the image position, the image is termed *virtual* (in contrast with a *real* image). Light rays coming from the tip of your nose, for example, strike the silvered surface of the mirror nearly at right angles, and are reflected directly back to your eyes along almost the same path. Likewise, in accordance with the law of reflection, rays coming from all other points on your face are reflected to your eyes from various portions of the mirror surface. Thus it appears to you that your face is located, not where it actually is, but at a point as far behind the mirror as you are in front of it. The rays obviously never pass through that apparent position back of the mirror; and the image is therefore virtual.

If you stand between two vertical plane mirrors, several images are always visible, because the light is reflected back and forth from one mirror to the other. The effect is especially weird if the mirror surfaces are parallel. Image after image of a bright object such as a lamp may be seen, each successive image apparently farther in the distance than the one before it. The distant images become dimmer, since part of the light is lost at each reflection back and forth between mirrors. No doubt you have observed this effect in barber shops or other places where large mirrors are hung on opposite walls of a room.

What are the conditions necessary in order that you may see your full length in a plane, vertical mirror? Let us suppose that you are about six feet tall. Obviously, in order to see your face, you must



How you see yourself in a "full-length" mirror. Note that the top of the mirror must be nearly even with the top of your head, and the mirror must be at least half as tall as you are.

put the top of the mirror nearly level with the top of your head—light rays coming from your forehead, for example, must travel out nearly horizontally and be reflected back to your eyes along almost the same path. But what about your feet? Since the angle of incidence equals the angle of reflection, a ray coming from your big toe must meet the mirror about three feet from the floor, in order that it may be reflected to your eyes at a height of nearly six feet. It turns out, then, that the mirror must be three feet tall (half your height), and the top of the mirror must be just about level with the top of your head. It does not matter in the least how near the mirror you stand, nor how far away you go. If this surprises you, you can test it for yourself with any full-length mirror.

Almost as large a fraction of the incident light is reflected from a sheet of white paper as from the shiny silvered surface of a mirror.

But you cannot see your reflection in a sheet of paper. Perhaps the reason is obvious. The paper surface is not perfectly flat and smooth, but contains many minute irregularities. The rays are reflected and scattered diffusely from the little hills and valleys, and image formation is impossible. Roughening removes the shine from any surface. Hence, for example, the use of face powder as a remedy for shiny noses. Similarly, ice broken up into many fine snow crystals differs considerably in appearance from a large cake of ice. A cake of ice is quite transparent; but each of the many tiny surfaces on the snowflakes reflects part of the light and scatters it. Additional reflection occurs from each successive layer of crystals, and the transmitted portion is eventually reduced to a negligible amount. As a result, snow is only translucent.

If a mirror surface is shiny but curved (that is, contains irregularities on a large scale), curiously distorted images are obtained. Your figure may be made to appear as long and thin as a bean pole or as short and dumpy as a barrel. No doubt you have seen mirrors of this kind in amusement parks or elsewhere, and have laughed about your funny appearance. When you look at yourself in such a mirror, it is interesting to recall the law of reflection to see just how any particular effect is produced.

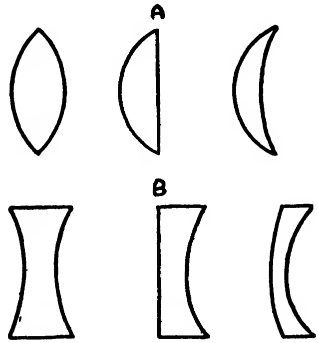
If a mirror is made saucer-shaped (that is, its surface is a portion of a sphere), then undistorted images are formed, but they are enlarged or reduced in size. Thus, rear-view mirrors for automobiles are often made convex in order to give small-sized images covering a wide field of view. Concave mirrors, like magnifying glasses, may be employed to form magnified virtual images; also under some conditions they may form *real images*. That is, the focused light rays actually pass through the image position, and the image may be projected on a screen. In respect to image formation, a concave spherical mirror is equivalent to a convex lens, whose optical properties we are now going to study.

III. *How Does a Lens Form an Image?*

As a basis for understanding the operation of all types of optical devices, let us see how a convex spherical lens forms an image. The lens may be curved outward on both sides like a magnifying glass (*double-convex*); it may be flat on one side and curved on the other like the lens in a flashlight (*plano-convex*); or it may even be concave on one side and convex on the other like a spectacle lens

(*meniscus* type). In any case, if it is thicker at the center than at the edge, it will give a certain type of image formation and it is called a *converging* or *positive* lens. The law of refraction (which fixes the degree of bending of the light rays on entering and leaving the lens) determines the path of each ray and the location of the image.

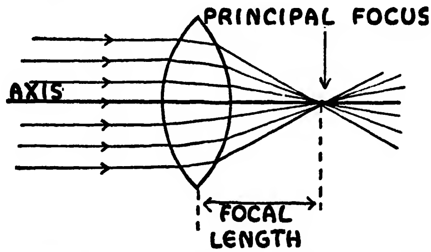
Let us stop and think what happens to a light ray as it passes through a double-convex lens. Suppose first that a ray strikes the center of the lens, in a direction perpendicular to the lens surfaces. This ray, which lies on the *axis* of the lens, is not deviated as it passes through. The light is merely slowed down while it is inside the glass.



(*A*) Types of converging (positive) lenses. (*B*) Types of diverging (negative) lenses.

Now, however, consider a ray that is traveling parallel to the axial ray but is off center. In accordance with the law of refraction, the ray is bent in toward the axis as it enters the glass, and it is bent inward still further as it emerges from the glass. It meets the axial ray at some point behind the lens. Furthermore, geometrical calculations, as well as experiments, show that all rays initially parallel to the axis meet (or focus) at approximately a single point, provided the area of the lens is not too large. The distance along the axis from the center of the lens to the point where the parallel rays meet is called the *focal length*. Thick lenses with sharply curved surfaces cause greater deviation of the rays than do thin lenses. The thick lenses therefore have shorter focal lengths and have a higher *power* than do the thin ones. The power of a lens has, of course, nothing to do with the definition of electrical or mechanical power—rate of energy supply. It is rather unfortunate to have two definitions for the same word, but usage has established them beyond repeal.

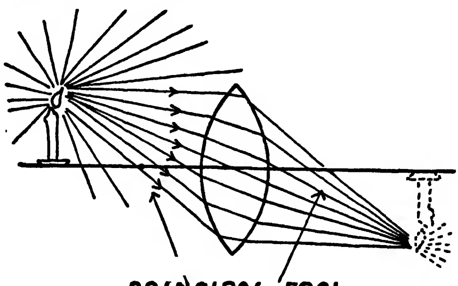
Rays coming from the sun or other distant objects are spreading apart at a very gradual rate; that is, they are nearly parallel. Hence, if you wish to find the focal length of a converging lens, you need only hold the lens up in front of a white wall or screen and project an image of a distant object on the wall. The distance from the



Focusing of parallel rays by a converging lens.

image to the center of the lens is approximately the focal length. If you use the sun as your object, you must be careful that you do not start a fire; because the rays are so concentrated at the focal point that they produce a great deal of heat. In other words, your lens becomes a "burning glass."

The real image of a distant object is very tiny and is located just behind the focal point. Thus, in picture taking, when the object is



Formation of a real image by a converging lens. Image and object are equal in size, because both are the same distance from the lens.

far away you set the film or plate of your focusing camera practically at the focal point of the lens. Now suppose that the object is moved up closer to the lens. Rays coming from any point on the object are diverging more rapidly when they meet the lens. The rays then focus at a position farther away from the lens than before.

In o [illegible] t moves closer, the image moves back and at the same time becomes larger. Thus, to focus your camera on a nearby object, you move the plate farther away from the lens, by extending the bellows. Incidentally, real images of the kind we are talking about here are always inverted (that is, are upside down), as you know if you have ever viewed the image formed on the ground-glass focusing plate of a camera.

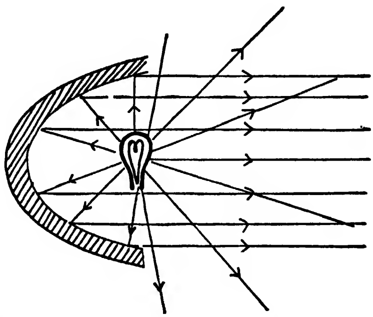
Now suppose that the object is brought up still closer to the lens. As it approaches the focal point, the image moves rapidly away from the lens on the opposite side and becomes greatly magnified. This is the arrangement that is used in the projection of motion pictures and magic lantern slides. The film or slide, strongly illuminated from behind, is located just outside the focal point of the projection lens. The image is formed far away and much magnified on the screen. The picture on the film must, of course, be inverted; then the image on the screen comes out right side up.

Finally, let us suppose that an object is brought inside the focal point of the lens. The rays now diverge so rapidly that the deviation produced by the lens is insufficient to converge them toward the axis. Instead, they continue to spread after passing through the lens, but they diverge at a lesser rate. In other words, the rays never come to a focus to form a real image that can be projected on a screen. But if you now place your eye up close to the lens and look at the object on the other side, you will see a virtual image, enlarged and erect. Employed in this way, the lens becomes a simple magnifying or reading glass. Just how the lens magnifies, we shall learn a little later.

Everything that has been said so far about positive lenses applies equally well to concave spherical mirrors. Only, in the case of a mirror, the rays are, of course, reflected back toward their source; and the real image is formed on the same side of the mirror as the object. If a bright light is placed just at the focal point of the mirror, then the rays are all reflected back in a direction more or less parallel to the axis of the mirror. In this way, light may be concentrated into a powerful searchlight beam. For best results, however, the searchlight reflector should be somewhat egg-shaped (mathematically speaking, *parabolic*), because a spherical mirror cannot reflect all of the rays back exactly parallel to the axis. The same trouble arises in focusing light with large spherical lenses.

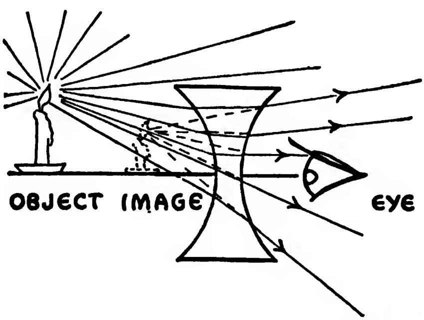
Later on, we shall discuss in more detail the difficulties resulting from this *aberration,* as it is called.

A word is in order here about the behavior of light rays when they pass through a *diverging* or *negative* lens—a lens thinner at the



Concentration of light in a searchlight beam. The source of light is located at the focal point of the concave, parabolic mirror.

center than at the edges. The rays are bent outward—away from the axis—and are therefore spreading more rapidly after passing through the lens than before. Hence, a negative lens by itself can never form a real image. By looking through the lens, however, one

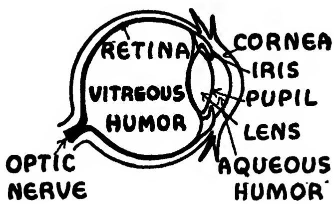


Formation of a virtual image by a diverging lens. When viewed by the eye, rays appear to come from the image.

can see a small virtual image of an object on the other side of the lens. In this way, a camera finder employs a negative lens (combined with a mirror) to give a miniature virtual image of the picture that will be recorded as a real image on the plate or film.

IV. *How Does the Human Eye Work?*

Now that we understand the formation of images by a lens, it is time to explain how the eye accomplishes its task of seeing. Optically, the eye is a simple mechanism, but its ability to adjust itself automatically to a wide variety of circumstances is truly remarkable. In a general way, the eye is quite similar to a photographic camera, in that a lens system focuses a real image on a screen (the *retina*) located at the rear of the eyeball. Sensitive nerve endings telegraph information to the brain concerning the fluctuations in light intensity and wave length on various portions of the retina. The brain then integrates these messages to give us the sensation of sight. The physiological and psychological processes involved are complicated and are something of a mystery. Here we shall discuss the optical



The construction of the human eye.

behavior of the eye only up to the point where the image is projected on the retina. Incidentally, the image is upside down, as are all real images formed by a single converging lens. The brain automatically inverts the picture for us; so we see things right side up.

Now about the construction of the eye. The nearly spherical eyeball is covered in the front by a tough, transparent membrane called the *cornea*. Back of the cornea is a watery material, the *aqueous humor*, which forms part of the lens system. Next comes the colored and non-transparent *iris*, which has a circular opening called the *pupil*. The iris serves as a diaphragm and automatically regulates the size of the pupil, admitting more or less light to the eye, depending on the brightness of the things we are looking at. Just back of the iris lies the *crystalline lens*, made of semi-solid transparent material having a greater optical density than does the aqueous humor. The curvature of the lens is adjustable; so that either near or distant objects may be sharply focused on the retina. Behind the crystalline lens, and filling the major portion of the eyeball, is a jelly-like mass of transparent material, the *vitreous humor*.

The most remarkable automatic adjustment of the eye is its power of *accommodation;* that is, the ability to focus on objects either far or near. The normal eye is able to bring a distant mountain into sharp focus on the retina and, a fraction of a second later, to form an equally sharp image of some fine print only a few inches away. From what has already been said about lenses, you realize that the optical system of the eye must undergo some change during this process of accommodation. Otherwise the image of the fine print would be formed far to the rear of the retina, and the print would be seen badly blurred. Now, accommodation might be provided for in either of two ways: the distance between lens and retina might be increased for viewing objects close up; or the curvature of the lens (that is, the power) might be increased without changing the distance between lens and retina. The former scheme (change of distance) is employed in focusing cameras. The eyes of animals and men, however, automatically change the curvature of the lens by means of reflex muscular action. The eye muscles allow the lens to flatten out when we look at distant objects, but quickly increase the curvature and thus shorten the focal length when we turn our eyes on nearby objects.

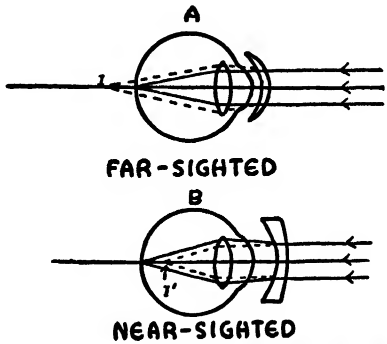
Another valuable feature of eye behavior is the *persistence of vision.* When an image is imprinted on the retina, we continue to see the image for about a tenth of a second after the source of the light is removed. This is due either to purely psychological effects in the brain, or to a time lag in the photochemical reactions that occur in the retina. An example of the persistence of vision is the blurred appearance of the spokes of a rotating wheel. Similarly, a glowing ember appears to leave a trail of light behind when it moves rapidly. Motion pictures depend for their effectiveness on the persistence of vision. As you know, sixteen or more separate pictures are flashed on the screen each second. After each picture, and before the next, the screen is darkened by a shutter in the projection machine. But the eye carries over the impression from one picture to the next, blending the separate images into an illusion of continuous motion.

V. *How do Spectacles Correct Faulty Vision?*

Considering the strenuous demands made on our eyes, no wonder the complex eye mechanism sometimes fails to function properly. Indeed, few of us fail to escape some form of eye trouble during our

lifetime. Occasionally, this trouble takes the form of serious disease in the retina, optic nerve, or other part of the eye; but more frequently, the difficulty is simply one of accommodation and can be remedied with the aid of spectacles.

If our eyes are normal, we are able to see clearly and without strain at all distances down to about 10 inches (25 centimeters) away. It is even possible to obtain a clear view of objects closer than 10 inches; but in doing so, adults at least are likely to be conscious of strain. Children's eyes are a little more flexible. In case we are afflicted with faulty vision, our eyes are unable to accommodate as they should. The difficulties with accommodation assume three common forms: ***far-sightedness, near-sightedness,*** and ***astigmatism.***

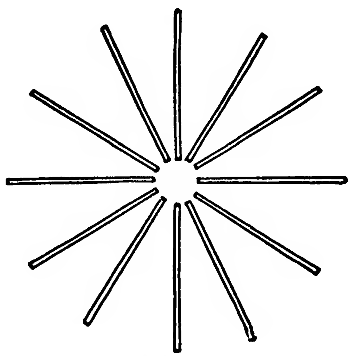


How spectacles correct faulty vision. (*A*) Far-sighted eye: without the aid of the positive lens, the images of near-by objects would be formed at *I* instead of on the retina. (*B*) Near-sighted eye: without the aid of the negative lens, images of distant objects would be formed at *I′*.

If a person is far-sighted, he is able to see distant objects clearly enough, but his eyes lack the power to accommodate for close-up work. The lens system of the eye is too weak, and the image of a nearby object is formed behind the retina. This condition may obviously be remedied by artificially strengthening the lens system—by placing in front of the eye a positive (magnifying) lens. This brings the images of close-up objects onto the retina where they belong. It may be necessary to remove the spectacles or to substitute weaker ones when looking at distant objects—hence, the widespread use of bifocals, in which two lenses of different power are incorporated in the same frame. Far-sightedness is really a normal fault in the eyes of older people. At least, the average person be-

comes increasingly far-sighted after he passes the age of 40 years. The muscles which control accommodation by changing the curvature of the crystalline lens lose their flexibility with age.

Near-sightedness, as its name implies, is just the opposite of far-sightedness. Nearby objects may be seen clearly, but distant objects appear blurred. Either the lens system of the eye has too short a focal length, or the eyeball is abnormally elongated—egg-shaped instead of spherical. Whatever the cause, the images of distant objects are focused in front of the retina. The power of the lens system may be decreased by fitting a concave (negative) lens in front of the eye. A near-sighted individual has one advantage over people with normal vision: without his spectacles, he is usually bet-



Have you astigmatism? Cover one eye and look at the center of the figure with the other eye. Unless all the lines appear equally sharp and black, you are affected with at least mild astigmatism.

ter able to distinguish details in objects held close to his eye. As we shall see later, this is due to an increase in size of the retinal image as the object approaches nearer to the eye.

The third common fault, astigmatism, occurs when the lens system of the eye is more sharply curved in one direction than the other. Hence, it is impossible to focus clearly at one time on both vertical and horizontal lines. The condition is corrected by fitting lenses that are just as unsymmetrical in curvature as are the eyes. The direction of greatest curvature in the spectacle lens must coincide with the direction of least curvature in the eye lens. The astigmatic spectacle lenses may be either converging or diverging, depending on the far-sighted or near-sighted tendency of the astigmatic eye.

Incidentally, here is a simple test that will enable you to determine the type of eye fault that any particular spectacle lens is intended to correct. Hold the lens up close in front of one of your eyes, and move it back and forth horizontally without changing the distance from the lens to your face. The virtual image of objects seen through the lens will move sideways in the *same* direction as the lens if the lens is negative and is intended to correct near-sightedness. The image will move in a direction *opposite* to the lens motion, if the lens is positive and is intended to correct far-sightedness. Now rotate the lens in front of your eye. If the image is distorted by the motion, then the lens is intended to correct astigmatism.

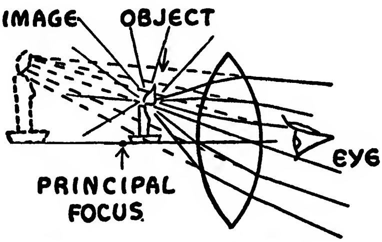
VI. *How Do Microscopes and Telescopes Aid Vision?*

Even individuals with normal eyes find it highly advantageous to employ optical instruments to bring out the fine details either in distant objects or in things close by. Therefore, we have telescopes, microscopes, opera-glasses, and other aids to vision—all of which contain combinations of lenses or of lenses and mirrors.

Before discussing the combinations, however, we must understand how a single lens is able to magnify nearby objects. First of all, let us see what is meant by the term *magnifying power,* as applied to a lens—or, for that matter, to any optical instrument. When we look at an object with the unaided eye, an image of a certain size is formed on the retina. If that image size can be increased by some means, it is evident that the details of the object should be more plainly visible than before. Suppose, for example, you are looking at a small printed letter, and a retinal image 0.1 millimeter high is formed by the eye alone. But suppose an image 0.5 millimeter high is obtained when the eye is aided by an optical instrument. Then the magnifying power of the instrument is said to be 5 diameters. You should note here that the magnifying power is customarily measured by the relative heights (or widths) of the magnified and unmagnified retinal images, and not by the relative areas of the images. If the linear dimensions are magnified by a factor of 5, the area is increased to 5×5, or 25, times its previous size. I mention this, because the manufacturers of cheap toy instruments sometimes claim absurdly large magnifying powers for their products. For example, they may claim that a microscope magnifies 1000 times; whereas the real magnifying power is equal to the square root of 1000, or about 30 diameters. Precision instruments actually do have

a magnifying power of a thousand, or even several thousand. The practical and theoretical limit is reached when objects separated by a distance approximately equal to the wave length of violet light (4×10^{-5} centimeter) are clearly discernible. With an optical microscope, it is impossible to distinguish objects much smaller than that.

But to return to the question of the magnifying glass—a single convex lens. From what we have already learned about image size, it is apparent that the closer an object is brought to the eye, the larger will be its image on the retina. But if the object is brought much closer than 10 inches from our unaided eye, the rays from the object diverge so rapidly that the lens system is no longer powerful enough to focus an image on the retina. Instead, the focus is behind the retina, and the image appears blurred. But suppose that the eye is



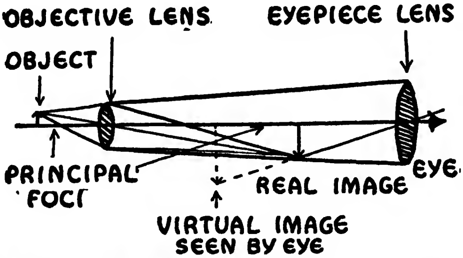
A single converging lens used as a magnifying glass. Rays coming from the object appear to originate at the enlarged virtual image. Note that the object must be located inside the principal focus.

aided by a converging lens, just like the spectacle lens for a far-sighted person, but more powerful. The object may be viewed from a distance closer than 10 inches—in fact, it may be brought just inside the focal point of the lens. But the enlarged virtual image seen by the eye is clear, and appears to be located a considerable distance away—10 inches or more.

As an example, suppose that we have a magnifying glass of focal length equal to 2 inches. Without the glass, an object to be examined must be held about 10 inches from the eye. With the glass, the object may be brought inside the focal point, or less than 2 inches away, if the lens is held close to the eye. The retinal image is then magnified by a factor of approximately 10/2, or 5 times. In general, then, the magnifying power of a lens of focal length f inches is given approximately by the relation $10/f$. If, instead of being

held close to the eye, the glass is placed some distance away (as is often the case when the magnifier is used as a reading glass), then the magnifying power is somewhat less.

Because of various aberrations, the magnifying power of a single lens is limited in practice to 20 or 30 diameters. For greater magnification, the *compound microscope* is employed. In its simplest form, this device consists of two lenses—the *objective* and the *eyepiece*—fitted into the ends of a metal tube. Both lenses have short

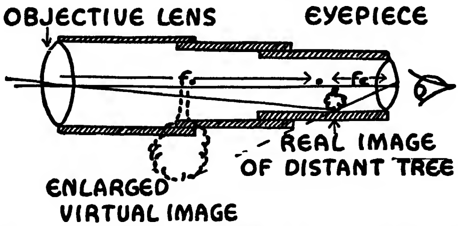


Elements of a compound microscope. The enlarged real image formed by the objective lens is further enlarged when viewed through the eyepiece. The final image is virtual and inverted.

focal lengths. The object to be viewed is placed just *outside* the focal point of the objective lens; and its image is therefore real, inverted, and much enlarged (like the image of motion picture film projected on a screen). This real image formed by the objective lies between the two lenses, and falls just *inside* the focal point of the eyepiece lens. The eyepiece thus behaves as a simple magnifier to give the observer an enlarged view of the real image formed by the objective. For example, let us suppose that the real image formed by the objective is 80 times the size of the object. If the eyepiece in turn magnifies this image 20-fold, the total magnifying power of the combination is 80×20, or 1600 diameters. The final virtual image seen by the observer as he peers through the eyepiece is always inverted.

As an aid in viewing distant objects, a single lens is very little help. But a combination of two lenses again serves our purpose. The refracting astronomical telescope, like the compound microscope, is made up of two positive lenses. But the objective lens is of long focal length; so the real image it forms may be as large as possible. Of course, the image is still small and is located just behind the focal point of the lens, because the object is so far away.

But the longer the focal length, the larger the image size. Again, as in the microscope, the eyepiece serves as a simple magnifier to enlarge the real image formed by the objective. The length of the telescope tube is about equal to the sum of the focal lengths of the objective and eyepiece lenses. It turns out that, with the aid of the telescope, the final retinal image is increased in size by the ratio of

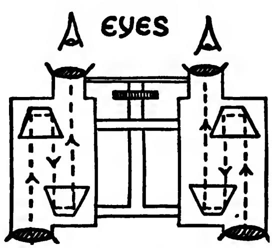


Elements of the astronomical telescope. Real image of a distant tree formed by the objective is enlarged by the eyepiece. The final image is virtual and inverted.

the focal lengths of the two lenses. In other words, the magnifying power is given by the following relation:

$$\textit{Magnifying power} = \frac{\textit{Focal length of objective lens}}{\textit{Focal length of eyepiece lens}}$$

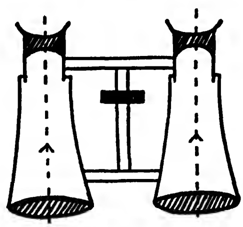
Since the final image as seen in the eyepiece of the astronomical telescope is inverted, telescopes made for viewing objects on the earth (spyglasses) are fitted with a third lens which serves to re-invert the image. In prism binoculars (field glasses), the same thing is accomplished by reflecting the light rays back and forth down the tube with the aid of prisms. This scheme has the added advantage of shortening the length of the instrument.



The optical system of prism binoculars. Lenses are both of the converging type, as in the astronomical telescope. The final image as seen by the eye is right side up.

Opera glasses (not to be confused with the optically superior prism binoculars) make use of a principle discovered by Galileo,

who invented the first telescope in the year 1609. The objective lens in an opera glass is a long focal length converging lens, just as in the astronomical telescope. The eye piece, however, is a negative (diverging) lens, located well inside the focal point of the objective. The result is an enlarged, virtual, erect image. The distance between objective and eyepiece lenses is less than in the astronomical tele-



Opera glasses. Eyepiece lenses are of the diverging type.

scope, and the instrument is therefore more compact. But the magnifying power is limited to 2 or 3 diameters (in contrast to 8, 16, or even higher for binoculars), because the field of view becomes very small if the power is made greater.

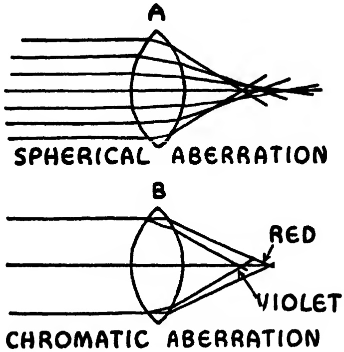
VII. *Why Are Optical Instruments Expensive?*

From what has been said so far, you are entitled to wonder why high-grade cameras, microscopes, field glasses, and other optical instruments should be so expensive. Often such instruments cost hundreds of dollars each. But things are not as simple as they seem. We have said that a single spherical lens forms clear undistorted images only if the diameter of the lens is small. Likewise, the size of the image must be small. If these conditions are not fulfilled, the images are subject to various forms of aberration or distortion.

We have already mentioned *spherical aberration:* rays striking the edge of a lens are brought to a focus at a different point (nearer the lens) from rays traveling near the axis. This difficulty is inherent in spherical lenses and mirrors. Likewise, *chromatic aberration* is unavoidable, in a single lens. Violet light is bent more than red in passing through the lens. The focal point is spread out into a sort of spectrum, just as though the light had passed through a prism or a raindrop, and the image may become a smeary, messy blur of color. There are other forms of distortion, all of which grow more serious as the lens becomes larger in diameter and shorter in focal length. These aberrations may be partially eliminated by

building up compound lenses out of two or more layers of different kinds of glass. But this process requires long and careful grinding, plus great pains in fitting and cementing the pieces together. It is no wonder that well-corrected lenses, especially those of large size, constitute the principal item of cost in high-grade optical instruments.

You might ask why large-size lenses are necessary at all. The diameter of the lens aperture has nothing to do with the focal length



Illustrating aberration in lenses. (*A*) Spherical aberration: rays passing through different parts of the lens are not all focused at the same point. (*B*) Chromatic aberration: violet light is bent more than red light in passing through the lens.

or magnifying power. These attributes depend only on the curvature of the lens surfaces. Why not use small-sized lenses in all our instruments? The answer is that large apertures are required if the instrument is to give bright, high-intensity images. Also, in some cases, high resolving power (the ability to make clearly discernible objects that are close together) and wide field of view are dependent on the lens size.

As an illustration of the importance of lens diameter, let us consider the matter of speed in photography. It is possible to take a picture without any lens at all, by simply putting a pinhole in front of the camera. But a long exposure of many seconds or even minutes is required. A candid camera, on the other hand, will take a picture on a clear day with an exposure of 1/1000 second or less. The brightness of the image, and hence the speed with which a picture is impressed on the film, depends on two characteristics of the camera lens: its light-gathering power (in other words, its area),

and its focal length. Obviously, the larger the area of the lens, more light it is able to gather in and bring to a focus—and brighter the image. Also, the shorter the focal length, the the size of the image, and the more intense is the illumination at given point in the image. Manufacturers usually rate the sp of their cameras in terms of the *f*-number, which is simply the ratio of lens focal length to lens diameter:

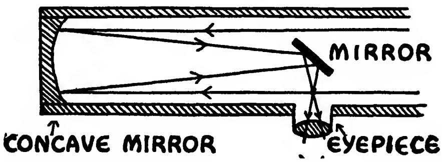
$$f = \frac{\textit{focal length}}{\textit{lens diameter}}$$

The time required for a satisfactory exposure under any particular conditions of lighting is then inversely proportional to the square of the *f*-number—that is, the larger the *f*-number, the longer the time of exposure. The square of the *f*-number enters the calculation because the brightness of the image, and hence the speed of the camera, depends on the *areas* of lens and image; that is, on the square of the lens diameter and the square of the focal length. To illustrate: suppose you can snap a picture in 1/100 second with a diaphragm opening having an *f*-number equal to 6.3; then, if you open up the diaphragm to *f*: 4.5, you can take the same picture in 1/200 second —because the square of 4.5 (about 20) is half the square of 6.3 (about 40). When possible, however, it is usually advantageous to take pictures with small diaphragm openings, because objects a little out of focus are then not blurred so badly (that is, the depth of focus is greater) and one does not have to take so much care in adjusting the camera.

Astronomical telescopes require large diameter objective lenses in order to obtain bright images; in order to distinguish fine details on the moon and the planets; and in order to separate the images of distant star pairs. Details of the structure of a single star are never seen; but the larger the area of the lens, the more light is gathered in and brought to a focus—hence, the brighter the image of a faint star. Because it is difficult to grind large lenses, it is customary in the largest telescopes to replace the positive objective lens by a concave parabolic mirror. With this construction, the light is reflected back up the telescope tube, and then off to one side (or once again back down the tube) by a small mirror or prism, where the image is observed with an eyepiece.

The largest telescope in the world is the new instrument soon to be completed at Mount Palomar in southern California. The concave objective mirror is 200 inches in diameter—nearly 17 feet.

The telescope "eye" will have a light-gathering power 600,000 times as great as that of the human eye. Hence, the astronomers will be able to see stars only one six-hundred-thousandth as bright as those we are able to see with our unaided eye. The magnifying power will be such that the moon, over 200,000 miles away, will appear to be less than 200 miles distant. And it will be possible to distinguish two craters less than 100 yards apart on the moon. However, Mount Palomar astronomers will probably not spend much



Newtonian type of reflecting astronomical telescope.

time looking at the moon with their new instrument. To an astronomer, the distant stars and nebulae are more interesting than the cold and lifeless moon.

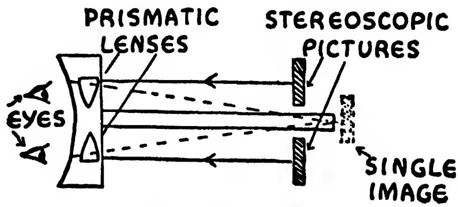
VIII. *How Does the Stereoscope Work?*

We are able to judge distance and perspective largely because we have two eyes instead of one. True, if you close one eye, you do not lose your sense of space perception entirely. But that is chiefly the result of long experience with your two eyes, plus certain other criteria such as the size of the retinal image. When we use both of our eyes, each eye sees from a slightly different angle; and the brain then merges the two slightly dissimilar images into an impression of depth.

Because photographs are flat, we are obliged to use our imagination to reconstruct in our minds the perspective of the original scene. The *stereoscope* is an optical device that enables one to recapture the illusion of three dimensions by means of a pair of flat, two-dimensional pictures. The pictures are taken simultaneously by two cameras placed a few inches apart, and the finished photographs are mounted side by side on a piece of cardboard. This card is then inserted in the stereoscope, just inside the focal point of a pair of wedge-shaped positive lenses. The lenses are held close in front of the eyes; so that each eye is able to see only one of the two pictures. Because of the prismatic shape of the lenses, the slightly-enlarged,

virtual images merge, apparently, into a single picture; and the objects in the photograph stand out clearly in three-dimensional relief. The effect is really startling, and it is rather too bad that stereoscopes are no longer fashionable. I am sure that our mothers and fathers spent many enjoyable hours in the parlor, peering, somewhat awed, at the flat pictures, magically transformed by the stereoscope into life-like three-dimensional panoramas.

As we noted in the last chapter, there is some possibility of extensive revival of stereoscopic effects in the realm of motion pictures. A pair of stereoscopic pictures must be projected on the screen, one of the pictures being viewed by the right eye and the other by the left eye. This may readily be accomplished if the light of one picture is polarized in a plane at right angles to the light of



The stereoscope.

the other picture, and if the observer views the screen through Polaroid spectacles. The axes of polarization of the two spectacle lenses are mutually perpendicular; that is, one of the lenses lets through light only from one picture, and the other lens transmits only the light from the second picture. If the screen is viewed without the aid of polarizing spectacles, the pictures appear to be a jumbled blur; but the spectacles result in sharp images that stand out clearly in three dimensions.

Normally, two cameras and two projectors would be required for stereo-movies; but special attachments are available which make it possible to put both pictures on a single film. Somewhat imperfect stereoscopic movies and lantern slides have been achieved by projecting red and green images that are viewed through red and green glasses. The Polaroid method is superior, however, and it also makes feasible colored stereo-movies.

The optical range-finder used in locating a target for artillery fire, and its smaller brother that tells you when your camera is properly focused, both operate in some respects like the human eyes.

The range-finder contains two mirrors a fixed distance apart; and the light reaching each of these mirrors from the distant object is used to form an image of the object. By turning one of the mirrors, the images are brought exactly together, and the angle between the mirrors is then a measure of the distance to the object. In the same way, we roll our eyes inward toward the nose in order to see a nearby object, and roll them less to see things farther away. The muscles that control these motions of the eyeballs report to the brain, and this report is one item of information the brain uses in forming a judgment of the distance. For all distances beyond a few yards, however, the axes of the eyes are practically parallel, and the changes of *convergence* are no longer large enough to be useful. Similarly, a range-finder is less accurate at large distances than at small distances.

IX. *What Causes a Mirage?*

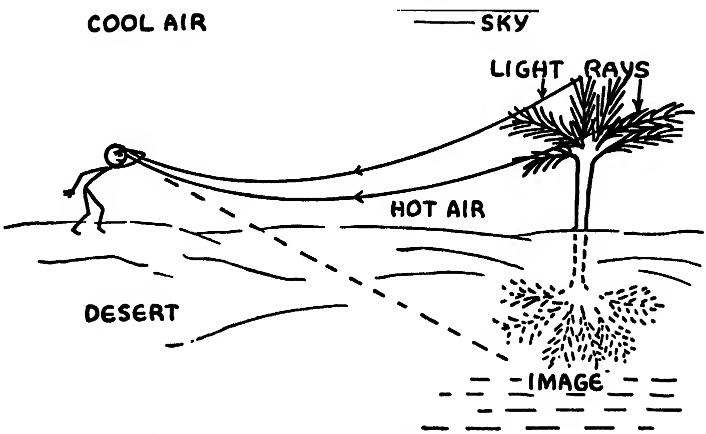
The refraction of light by a gas is never great; and light rays are bent very little when they pass through a region where the optical density of the air is changing. Nevertheless, refraction in the atmosphere is responsible for some interesting natural phenomena.

You are familiar with the appearance of "heat waves" rising from a hot stove or pavement. This shimmering is a refractive effect caused by varying density in the rising currents of hot air. Objects located behind these convection currents appear distorted, just as though the light had come through window glass with irregular surfaces. Twinkling of the stars is due to the same cause—motion and changes in density in the upper atmosphere.

You are perhaps aware that the sun is visible for some time after it has set. Since the sun is about 92 million miles away, some 8 minutes elapse before the last rays reach us after the sun's disk has actually passed below the horizon. But, in addition, the sun's rays are bent as they come into the earth's atmosphere out of empty space. The law of refraction requires that the rays tend to follow the curvature of the earth. Therefore, aside from the matter of time for the light to reach us, the sun appears to be higher than it actually is. Since the bending effect increases as the sun gets closer to the horizon, the sun's disk often appears flattened on the bottom just before sunset. Light reaching us from the lower portion of the disk is bent more by the atmosphere than is light coming from the upper part.

Probably the most interesting of all atmospheric refraction phenomena is the mirage. Not many of us have the opportunity of

viewing this illusion in its full glory; for it appears to best advantage on wide expanses of hot desert land. But on warm sunny days, we have all seen what appear to be patches of water ahead of us on a dry road. These, like the mirages of the desert, are virtual images of the sky. They are formed by refraction of light rays in a hot rarefied layer of air near the earth. As light from the sky enters this region of lower density the rays are bent into the shape of a bow, concave upward. Hence the rays never reach the ground, but are refracted back up again to our eyes. Thus it appears to us that the rays have



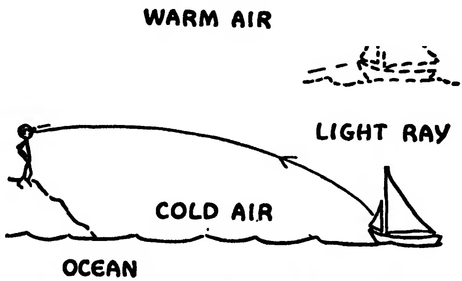
The mirage. A distant tree on the desert appears to be reflected in a lake. The "lake" is only an image of the sky.

come from the ground instead of the sky. Sometimes, distant mountains, even buildings and trees, may be seen as mirages. Since the images are inverted, these objects appear to be reflected in the imaginary "lake" formed by the mirage of the sky. The illusion is so real that thirsty travelers on the desert have been lured into following a constantly retreating mirage until they finally dropped from exhaustion.

Sometimes it happens, especially over cold bodies of water, that the sun's rays heat the upper layers of air hotter than the air near the earth. The light rays from objects located on the earth are then bowed into a path with the concave side downward. These objects then appear to be floating in the sky. The effect is known as *looming*, and is perhaps even more weird than the mirage. An image of a ship above the ship itself is often visible at sea. I recall, on the Pacific

Coast, having occasionally been startled to see Catalina Island apparently floating in the clouds, far above its customary position on the surface of the ocean. Because of looming, it is sometimes possible to see objects which would normally be invisible below the horizon.

We might mention here some other optical phenomena—*coronas, halos,* and *sundogs*—that are due to the bending of light rays in the atmosphere. Coronas, commonly known as rings around the sun and moon, are due, not to refraction, but to diffraction (see page 154) by fog particles suspended in the air. Doubtless you have observed the same effect in looking through a fogged window or windshield at a distant light. The bright circular ring may be partially colored, but not as distinctly as in the case of the rainbow. The



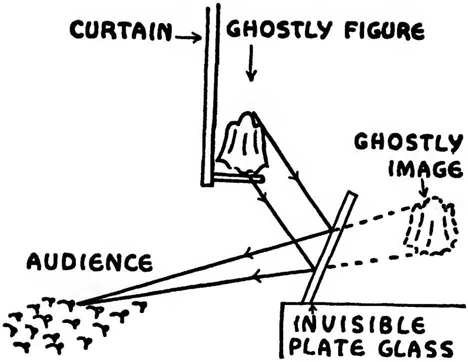
Looming. An image of the ship appears to be floating in the air.

diameter of the ring depends on the distance of the moisture particles from the observer, and on the size of the particles.

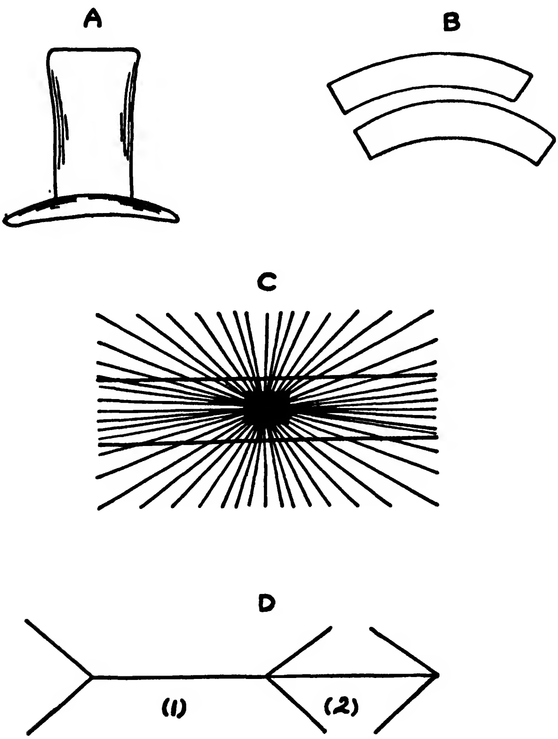
Halos, sundogs, and other rare phenomena of a similar type are formed in much the same manner as a rainbow; but the reflection and dispersion take place in ice crystals instead of spherical raindrops. Since the crystals may have various forms and shapes, the phenomena differ markedly in appearance from one time to the next.

X. *What Are Optical Illusions?*

The term *optical illusion* is rather vague, and might, I suppose, be applied to any optical effect in which things are not just what they seem. As we said earlier, virtual images formed by mirrors and lenses might be called optical illusions. Certainly, stereoscopic effects and mirages could be placed in the same category. We are more likely, however, to limit the use of the term either to the cases wherein we are deliberately tricked by professional magicians, or to errors in per-



One way of mateiializing a ghost on the stage.



Optical illusions. (*A*) The hat is as wide as it is high. (*B*) The arcs are of equal length. (*C*) The heavy lines are really straight. (*D*) Lines (1) and (2) are of equal length.

ception judgment which the psychologists call ***space errors*** or ***space illusions.***

As a simple example of the magician's art, let us consider how theater ghosts may be made to appear on the stage. The figure to be materialized is hidden from the direct view of the audience either in a pit or high up behind a curtain at the front of the stage. An image of the figure is reflected in an invisible sheet of plate glass; and by tilting the glass at the proper angle, the "ghost" will appear to be floating in the air. The degree of materialization is adjusted by the intensity of the spotlight thrown on the actual figure. The glass that reflects the image is transparent and entirely invisible to the audience if its surfaces are highly polished and its edges are hidden from view. The old saying, "it's all done with mirrors," is not so far wrong in the case of many spectacular tricks performed by famous magicians.

Illusions that involve errors in judgment of shape and distance are known to all of us. Architects and sculptors often find it necessary to distort their creations in order to make the result look natural. Straight lines sometimes appear to be curved; parallel lines frequently seem to be non-parallel; vertical distances are commonly judged to be greater than the same horizontal distances; vertical stripes on our clothes make us look tall and thin; horizontal stripes make us look short and fat—there are many effects of this kind.

Psychology offers numerous theories to account for these space illusions. Since perception is a highly complex process, it seems likely that no one of the theories is more than partially correct.

CHAPTER NINE

ABOUT HEAT AND COLD

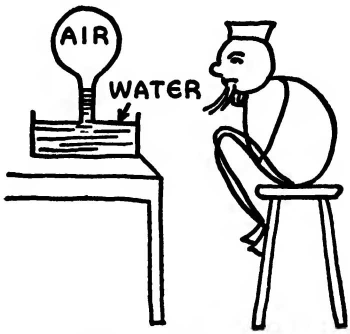
I. *How Is Temperature Measured?*

If someone asked you the simple question, "How is temperature measured?" you would probably be slightly surprised and would answer, "Why, that's easy: with a thermometer, of course." True enough, but it is not quite so simple as it sounds. Perhaps you will agree, when you hear a little about the history of temperature measurements.

Before the early part of the seventeenth century thermometers were unknown, and men relied solely on their sense of touch to measure temperature. But the sensation of hot and cold is often a poor standard of temperature. No doubt you have had the experience of feeling chilly when the thermometer read 70° or even 75° F. On the other hand, you have felt comfortable, even hot, in the sunshine, when the thermometer read as low as 40° or 50° F. Also, you have walked across the cold linoleum in your bare feet, and then were glad to step on a wool rug that felt pleasant and warm—though the rug and the linoleum were actually at the same temperature. An iron tool lying in the summer sun becomes hot enough to burn you. But the wooden handle of the tool, at the same temperature, feels only warm.

The reason for these paradoxes is not hard to find. Linoleum and iron are good conductors of heat. Hence, they rapidly cool or heat to their own temperatures the soles of your feet or the palm of your hand. If you grasp a piece of hot iron, heat can come out of the iron to the nerve-endings in the skin of your palm much faster than it can escape to the bulk of your hand; and the nerve-endings register this unbalanced arrival of heat by the sensation: hot. If the iron is cold, heat goes into it readily from the nerve-endings, and the sensation is one of cold. Wool and wood, on the other hand, are poor conductors of heat; they carry heat to or from the nerve-endings so slowly that the sense of hot or cold is relatively little stimulated.

The sensation of hot or cold is certainly an unreliable measure of temperature, but there is no record that the learned men of ancient times knew any better way of measuring it. One of the first thermometers was invented by our old friend Galileo. His simple device was scarcely more satisfactory than the sense of touch, because the reading varied with the atmospheric pressure as well as with tempera-



Galileo's thermometer.

ture. But Galileo did not know this. His thermometer consisted of a long-necked glass flask, inverted, with the neck partly immersed in water. A little of the air in the flask was allowed to bubble out; so that the height of the column of water in the neck rose and fell as the air in the flask contracted and expanded.

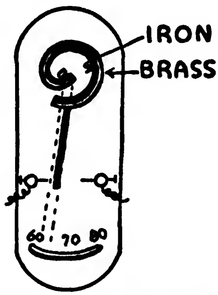
Gas thermometers, acting on this same principle, but with the effect of changes in atmospheric pressure eliminated, are still used today. They are, in fact, the most accurate of all thermometers, and are employed in laboratories for standardization; but they would hardly be convenient for everyday use.

Our common thermometers depend on the expansion of a liquid like mercury or alcohol (the alcohol is dyed red so that it can be seen easily). The greater part of the liquid is contained in a glass bulb; but as the bulb is heated, a small thread of the liquid rises in a glass tube of small bore. The glass bulb itself expands as it becomes hotter; but the liquid expands more rapidly, and this excess expansion of the liquid gives us the temperature reading on the scale.

All solids expand when they are heated; though the expansion is less than for liquids. You are aware, perhaps, that cracks are left in cement pavements, in steel bridges, and between the ends of rails, in order to allow for expansion at high temperature. A steel bridge

a thousand feet long may be about a foot longer in summer than in winter. If provision were not made for expansion, such a structure might buckle.

Thermostats, for opening and closing electrical circuits, for controlling the size of a gas flame in ovens and water heaters, and for many other purposes, commonly make use of the expansion of metals. One type of thermostat depends on the unequal expansion of two different metals. Brass, for example, expands more than iron. So if a strip of brass and a strip of iron are firmly riveted together at one temperature, the combination becomes curved at any other temperature. The iron side will be concave at a higher temperature, the brass side at a lower temperature. Obviously, such a bimetallic strip may be made to serve as a switch for turning on or off an electric current at a designated temperature.



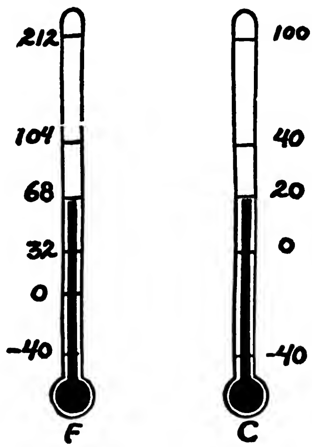
One type of thermostat. A bimetallic strip changes its curvature with changing temperature and closes an electric circuit.

But to return to the subject of temperature measurement: Whatever the method chosen, a standard temperature scale must be provided, if the reading of the thermometer is to mean anything. The various temperature scales in common use today are entirely arbitrary. Two fixed and reproducible points have been chosen; then the temperature interval between these two points has been divided into a number of sub-intervals or degrees.

The choice of fixed points presented a real problem to the early makers of thermometers. All sorts of standards were suggested, including the melting point of butter, body temperature, and the temperature of warm milk fresh from the cow. But nowadays, the freezing point of water, and the boiling point of water at atmospheric pressure at sea level, are the universal standards. On the Centigrade scale (the one used in most European countries except

England, and in all scientific work), ice melts at 0°, and water boils at 100°.

On the Fahrenheit scale, which is the one commonly used in the United States and England, ice melts at 32°, and water boils at 212°. The interval between freezing and boiling is thus divided into 212 minus 32, or 180 degrees.*



Comparison of the Fahrenheit and Centigrade temperature scales.

Although today the Fahrenheit scale is based on the freezing and boiling points of water, this was not always so. When Fahrenheit first devised the scale named after him, he chose as 0° the lowest temperature that he could obtain in the laboratory at that time—the temperature of a mixture of ice and salt. The other fixed point was normal body temperature, which he called 24°. Later, Fahrenheit's degree was divided into four parts, making body temperature 96° instead of 24°. Our modern scale has apparently been shifted somewhat, because normal body temperature is now 98.6° F.

Even from this sketchy discussion, you can see that the measurement of temperature is of surprisingly recent origin, and that it has presented considerable difficulty. But that is the way with most scientific achievements that we ordinarily take for granted.

* In order to change from Centigrade to Fahrenheit, or vice versa, the following formula is useful: °F. = 9/5 °C. + 32.

II. *What Is Heat?*

From everyday experience, you would probably concede that *temperature* is a measure of relative hotness and coldness. But do you recognize the distinction between temperature and *heat?* Heat is something contained in a body, which makes the body hot. Lack of heat means that the body is cold. Temperature is a measure of the contained heat, but is not in itself heat.

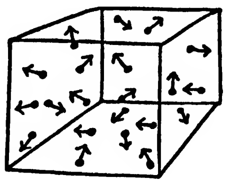
Today we are well aware that *heat is a form of energy.* In the light of present-day knowledge, this fact is so self-evident that physicists are inclined to make uncomplimentary remarks about the die-hards of scarcely a century ago who still believed that heat is an imponderable (weightless) fluid. But this *caloric theory* of heat, as it was called, was by no means a bad theory in many respects. People knew, for example, that heat flows from a hot body to a cold body, and that eventually both bodies come to the same temperature. This was easy to explain: a hot body contains more of the heat fluid (caloric) than a cold body; and the fluid flows from hot to cold. Again, people knew that it takes more heat (caloric) to raise the temperature of a pound of water 10° than a pound of iron: the water just naturally had a higher caloric content than the iron. In fact, the caloric theory could be made to explain almost all that was known about heat except one thing: the production of heat by friction.

When you apply the brakes to stop your automobile, the friction between drums and bands develops considerable heat. Prolonged application makes the drums very hot and may cause smoking and burning of the bands. But, normally, there is very little permanent change in either bands or drums. Nor does any other body in the neighborhood become cooler. Therefore, the heat cannot very will be something (a fluid?) contained in the materials and simply liberated by the friction. Rather, it must be something created by the friction—something that appears when the kinetic energy of the automobile is decreased.

Many carefully performed laboratory experiments (similar in principle to the heating of the brakebands and drums by friction) finally demonstrated to even the most skeptical that each time mechanical energy disappears as a result of friction, a corresponding amount of heat is produced. Later, a similar equivalence between electrical energy and heat was discovered. The conclusion was inescapable that heat must be a form of energy.

Now, heat is usually measured in *calories,* a purely arbitrary unit chosen on the basis of the most useful substance in early heat measurement—water. The calorie is the quantity of heat required to raise one gram of water through a temperature of one degree Centigrade.

The number of calories needed to raise one gram of any substance through a temperature of one degree Centigrade is called *specific heat.* The specific heat of water is evidently just one calorie per gram. The specific heat of most other materials is less than for water. Grain alcohol, for instance, has a specific heat of only 0.6 calorie per gram. This is the reason why your automobile radiator often heats up faster in winter when it contains anti-freeze solution than in summer when it contains pure water. The high specific heat of water makes oceans and lakes great reservoirs of heat energy—a fact of special significance in the determination of weather conditions, as we shall see in the next chapter.



The kinetic theory picture of a gas. Molecules moving at random create pressure by collision with each other and with the walls.

If you are ready to agree that heat is a form of energy it still remains to be explained just how this energy is stored up in a material. The answer is simple: heat is contained in the form of atomic or molecular motion. A hot stove feels uncomfortable to the touch, because the atoms of the iron are vibrating rapidly and are transferring some of their energy by direct contact to the atoms and molecules of your fingers, so as to stimulate the nerves. The molecules of a solid or a liquid cannot readily move very far; hence, their heat energy is stored up principally in the form of vibratory motion. This is not true in a gas; consequently, a study of the behavior of gases gives us a simple insight into the true nature of heat energy.

According to the *kinetic theory,* a gas consists of myriads of inconceivably small molecules, all darting frantically hither and yon at a high rate of speed. The molecules collide with one another and with solid surfaces, bouncing off like perfectly elastic billiard balls.

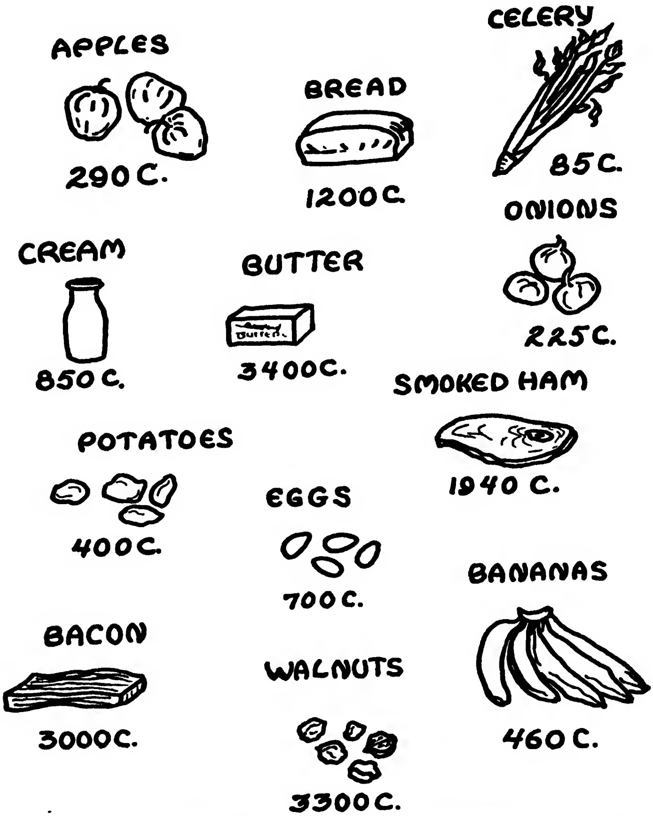
It is this continuous rain of billions upon billions of molecules pounding against a surface that is the ultimate cause of gas pressure.

The speed of the molecules depends on the temperature. At 0° C., air molecules on the average travel at the tremendous rate of 1100 miles per hour; and each molecule makes more than five billion collisions with its neighbors (or against the walls of the containing vessel) each second. The total heat energy of the gas is simply the *kinetic energies* of all the separate molecules added together. As the temperature is raised, the kinetic energy is increased, the molecules move faster, and greater pressure is created by the bombardment against the walls. As a gas is cooled, it loses heat energy and, hence, the average speed of its molecules decreases. At 273° below zero Centigrade (−460° F.), all molecular motion would cease, and the volume as well as the pressure of the gas would theoretically become zero. This temperature is known as the *absolute zero*. In practice, before absolute zero is reached, all real gases first liquefy, then solidify. Oxygen, for example, condenses to a liquid at −183° C.; helium, the most difficult of all gases to liquefy, boils at −269°—only 4° above the absolute zero.

Very likely, you have pumped up a tire with a hand pump and have noticed that the barrel of the pump became hot. Since the temperature of a gas depends only on the speed of its molecules, and not on their density, you might wonder why compression causes heating of the gas. But the very motion of the piston gives an additional kick to the molecules. They bounce off the oncoming piston surface with increased speed in all directions as a result of collisions. If the gas is an inflammable mixture, very high compression may cause an explosion. This spontaneous combustion is put to practical use in the Diesel engine, where the mixture of air and fuel is fired by the high temperature of compression alone, without the aid of an electric spark.

Although heat energy and mechanical energy can each be changed into the other, there is a clear distinction between the two. For example, a mass of air moving along as a wind has mechanical energy, which can be used to turn a windmill or propel a sailboat. But if the wind blows on an unyielding wall and is turned back on itself and thus finally stopped, the organized mass motion will be changed into disorganized, chaotic motion of the individual air molecules. The average molecule has the same speed in the stopped air as in the original wind, but there is no longer any ordered motion

common to all the molecules. Instead, each one is darting about along his own choice of direction. When energy reaches this disorganized state, being parcelled out among individual molecules, it is heat energy. Mechanical energy or electrical energy can be completely converted into heat. There are ways, as we shall presently



The energy value in large calories provided by *one pound* of various foods.

see, for converting the random motions of molecules back into organized mechanical motions—but the conversion of heat into mechanical or electrical energy is never complete.

Sometimes, the *large calorie*, or *kilogram calorie*, is employed as a unit of heat energy. This is equivalent to 1000 of the gram calories we talked about earlier. The energy provided by various foods is usually expressed in terms of the large calorie. When you say, for

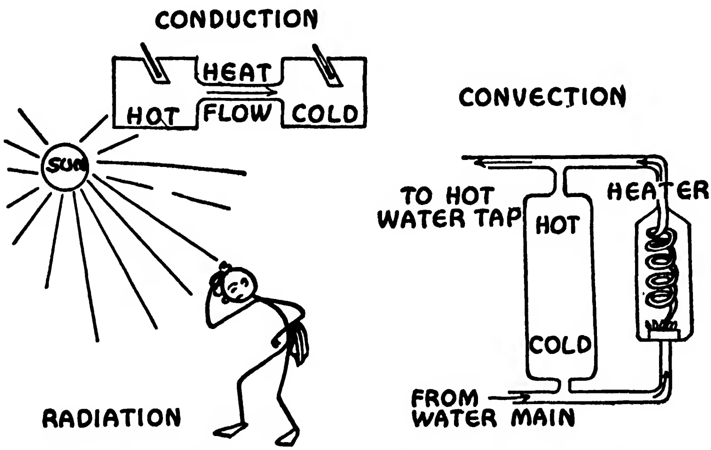
example, that a pound of butter contains 3500 calories, you mean that when the butter is completely burned up by oxidation, 3500 large calories of heat will be produced. This energy is not present as heat in the butter itself, of course—so much heat would be more than enough to melt and vaporize the butter. The energy appears only when the butter combines chemically with oxygen. Meanwhile, it is stored-up chemical energy. In the same way, we can calculate that a charged 6-volt storage battery of 100 ampere-hours capacity contains approximately 456 large calories of stored chemical energy. If the battery is completely discharged through a resistance, this much heat will appear. These cases illustrate that the calorie is an appropriate unit for energy in any form, though it is defined as a unit of heat energy.

III. *How Is Heat Transferred?*

Since heat is contained in a substance as molecular motion, it is not surprising that this motion is transferred from a hot body to a cold body by direct contact. Fast-moving molecules tend to speed up their slower neighbors on collision. This method of heat transfer is called, simply, *conduction*. Some materials are good conductors of heat; some are poor. Generally speaking, metals are excellent conductors; and the best conductors of electricity are also the best conductors of heat. Thus aluminum, a good electrical conductor, is likewise a good conductor of heat; and aluminum pots and pans (particularly the heavy cast ones) are excellent for cooking purposes, because they heat rapidly and uniformly. On the other hand, materials like wool, sand, asbestos, cork, and still air are poor conductors of heat; hence they are valuable for insulation of our houses, our refrigerators, and our bodies against either heat or cold.

In gases and liquids another process of heat transfer is very effective; namely, convection, or the rising of heated fluids in accordance with Archimedes' Principle of buoyancy. We have seen already how this works in the case of drafts in chimneys, and in the shimmery appearance of the air above hot objects. As we shall see in the next chapter, wind is usually caused by convection currents in the atmosphere. Likewise, gliders can rise to an altitude of thousands of feet and can fly many miles with the aid of updrafts in the atmosphere. Such convection currents moving either up or down cause the unpleasant "bumps" in the air that often annoy aeroplane passengers, and even make them airsick.

In a hot water tank, convection makes it possible to heat the top portion of the water while the bottom remains cold. The warm, less dense water rises to the top through the heating coils, and "floats" on the cold water until it is drawn off. Similarly, hot-air and hot-water heating systems bring heat up from the furnace in the basement by means of convection. Likewise, in the old days, water was circulated in automobile cooling systems by thermal flow alone. As the water around the cylinders became heated, it rose to the top of the radiator; while water that had been cooled by the fan flowed in from the bottom to take its place. Model-T Fords were cooled by a system of this type. Nowadays, in all makes of cars, convection is aided by circulating pumps.



The three methods of transferring heat: *conduction, convection, radiation.*

So much for the transfer of heat through material media. But we also receive heat through empty space from the sun. Evidently not all the heat in the universe is stored up in the form of atomic and molecular motion. As a matter of fact, every object—hot or cold—constantly emits long wave length infra-red heat rays. As we saw in Chapter Seven, this radiation is similar to visible light except that its wave length is greater. To our other two means of heat transfer—conduction and convection—we must therefore add a third very important method; namely, *radiation*. While transfer of heat by conduction or convection requires the presence of a material medium, heat radiation travels most readily through empty, evacu-

ated space. Radiation may, however, be transmitted through any medium that does not absorb it.

All objects emit heat rays; but it is a matter of everyday experience that hot objects radiate more heat than do cold ones. The quantity of energy radiated increases very rapidly with increased temperature. In fact, it goes up as the fourth power of the absolute temperature. This means that doubling the absolute temperature results in $(2)^4$, or 16, times as much emitted radiation.

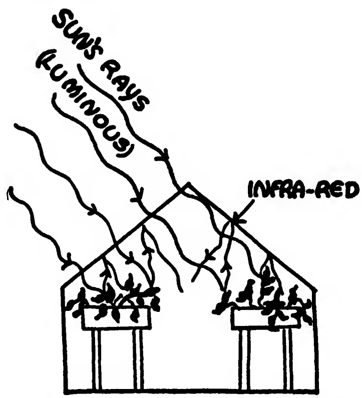
An object at the same temperature as its surroundings absorbs heat just as fast as it loses heat. But things exposed to the rays of a hot body like the sun become continually warmer until conduction, convection, and radiation combined, serve to carry off heat as fast as it is absorbed. For example, a thermometer bulb, exposed to direct sunlight, becomes much hotter than the surrounding air. This is the reason why temperatures are always recorded as "so many degrees in the shade." A reading taken with the thermometer in the sun has no real significance.

Some materials, particularly those of a dull, dark color, are good absorbers; that is, they absorb nearly all the heat that falls on them and reflect very little. These same materials likewise radiate heat effectively. On the other hand, things that are light-colored or shiny reflect most of the radiation and absorb very little. Such poor absorbers are likewise poor emitters.

The pipes and tanks of solar water heaters are always painted a flat black in order that they may absorb as much heat as possible from the sun's rays. Dark-colored roofs and clothes should be avoided, however, if you wish to keep cool in the summer time. People in the tropics usually wear white clothes to minimize absorption of heat. But dark clothes will help you to keep warm in the winter sun. Similarly, ice and snow will disappear from an asphalt pavement before they will from white concrete. The dark asphalt absorbs more heat. Snow will often melt away from under a leaf sooner than it will out in the open, because the dark leaf is a better absorber than the white snow exposed directly to the sun. In cities, old snow surfaces are pitted and uneven, the bottom of the pits being composed of specks of soot or dust that have been heated by the sun's radiation and have melted the snow below them.

Because of a peculiar property of glass, the interior of a greenhouse is maintained by radiation at a temperature well above the outside. The glass, being transparent to visible light, admits sunlight

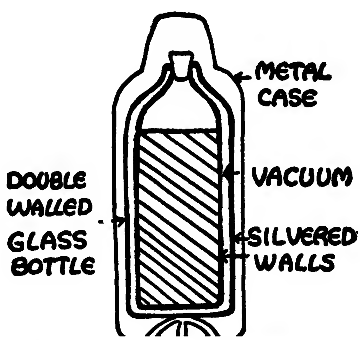
to the greenhouse. The light is largely absorbed by the plants and other objects inside. These, in turn, reradiate the energy; but, being



A glass-covered greenhouse serves to trap radiation supplied by the sun.

cool, they emit only long wave length heat rays. Glass is opaque (nontransparent) to this heat radiation; hence, the energy is partially trapped inside the greenhouse. The heat can, of course, escape by conduction through the walls, but not by radiation.

A high degree of heat insulation is attained in the thermos bottles, which picnickers and others find so valuable for keeping coffee hot



Construction of the thermos bottle.

or lemonade cold. The bottles are double-walled, with the air evacuated from the space between. The vacuum prevents loss of heat by conduction or convection, except in a small region around the neck. Radiation, either inward or outward, is largely eliminated by

silvering the walls. Shiny surfaces, you recall, are poor radiators and poor absorbers of heat. Vacuum bottles of this type are the most efficiently insulated vessels known; but they are rather expensive, especially in the larger sizes. The lower-priced food jugs do not keep things hot or cold nearly so long, because they have no evacuated space. They are merely porcelain containers surrounded by some heat-insulating material.

A word about the apparent radiation of cold: You have probably held your hand up close to a piece of ice and have gained the impression that the ice was radiating a blast of cold, just as a hot stove radiates heat. Such is not the case. Actually, the ice radiates heat—but your hand (at a higher temperature) radiates more heat. Hence, heat radiated (and conducted) from your hand is not compensated by a return flow from the ice. Your hand feels cold because it is continuously losing more heat than it gains.

IV. *How Do Solids Disappear Without Melting?*

Usually, when a solid material is heated to a high enough temperature, it melts—although some solids burn before they melt, if they are heated in the air. A few chemical compounds and mixtures like gunpowder, react violently and explode, even in the absence of oxygen. But some solids neither melt nor burn, nor do they explode when they are heated—they simply vanish into space in the form of a vapor. This direct transformation of a solid into a gas is termed *sublimation.* It is analogous to the evaporation of a liquid.

Sublimation is perhaps more common than we realize. For example, moth balls (naphthalene or camphor) or paradichlorobenzene moth crystals disappear if they are left in the open for a long enough time. Likewise, tungsten filaments slowly sublime and blacken the inside of our light bulbs.

Even ice sublimes, though at a very slow rate. Perhaps you have noticed that ice and snow gradually disappear from sidewalks and streets, even when the weather is so cold that melting is out of the question. The ice changes directly into water vapor without going through the customary liquid stage. Days or weeks pass, however, before a noticeable quantity of ice disappears in this fashion.

The modern refrigerant, dry ice, is convenient because it sublimes and leaves no messy liquid behind. Dry ice is made by solidifying carbon dioxide, the same gas that forms during most burning processes, and that causes the fizzing of carbonated beverages. At

atmospheric pressure, carbon dioxide exists either in the form of a gas, or as a very cold solid (dry ice, at $-80°$ C.). Only at high pressures can it be liquefied. Contained in steel tanks, the liquid form is supplied to fountains for making sodas. Carbon dioxide is also used for inflating life-rafts quickly. A small pressure tank containing the liquid is attached to the deflated raft and is opened when the raft has to be used. A pint of the liquid, expanded to the gaseous form, is enough to fill a raft that will support several hundred pounds.

Incidentally, dry ice is so cold that it must be handled with care. It freezes the flesh very readily and, like severe frostbite, can cause blisters and lesions that appear quite similar to burns. Curiously enough, extreme heat and extreme cold are much alike in their effect on unprotected human flesh.

V. *What Happens When Ice Melts?*

Although ice can sublime at a very slow rate, it normally disappears by melting. But melting is by no means a rapid process, even when the ice is in warm surroundings. Covered with sawdust or some similar heat-insulating material, a supply of ice can be kept all summer. Melting takes place slowly, because a large quantity of heat is required. In fact, with no change in temperature, each gram of ice absorbs 80 calories when it melts. This is enough heat to raise the temperature of a gram of water through 80° C.—in other words, to heat the water from room temperature to the boiling point.

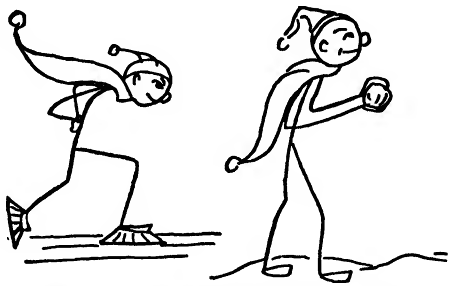
We can see now why ice is so effective in keeping things cold. In melting, it absorbs large quantities of heat, without itself becoming any warmer. For this reason, a small piece of ice is much more effective in cooling a cup of coffee than is an equal mass of cold water.

The reverse process of freezing also requires considerable time, for the obvious reason that 80 calories must be dissipated—carried away by neighboring bodies—for each gram of water that solidifies to ice. Thus, while they are freezing, lakes and other large bodies of water give off much heat, and keep the surrounding air comparatively warm.

Some substances contract when they freeze; others expand. Since ice floats, with about one-tenth of its volume above the surface, water is evidently the type of material that expands on freezing. This is unfortunate in one respect: when water pipes freeze, they often burst. On the other hand, it is most fortunate for many rea-

sons. If ice were heavy enough to sink to the bottom of oceans, lakes, and rivers, most forms of animal and plant life would be unable to survive in these bodies of water. Also, the ice, once formed, would melt very slowly or not at all. Jagged, invisible peaks of ice lying in wait beneath the surface would make navigation a far more hazardous business than it is.

Though a number of liquids are like water in that they expand on freezing, only a very special property of water makes it possible for ice to form initially on the surface rather than on the bottom of a pond or vessel. In general, things contract (hence, become more dense) when they are cooled. Water obeys this rule down to a temperature of 4° C. (about 39° F.). At that point, however, water attains its maximum density, and begins to expand as it is cooled further. In accordance with Archimedes' Principle, the water of



Melting of ice by pressure provides lubrication for skating and causes snowballs to stick together.

greatest density (at 4° C.) sinks to the botton. The colder water (below 4° C.) rises; and this cold top layer naturally freezes first. At the bottom of deep lakes, the water often remains at practically 4° C. the year round, since water that becomes either cooler or warmer rises to the top.

The addition of foreign materials, such as salt or sugar, lowers the freezing point of water. Sea water freezes at – 2.5° C. instead of at 0°. Because of the presence of sugar and other dissolved materials, ice cream cannot be frozen when surrounded with pure ice. Instead, a mixture of salt and ice, at a temperature considerably below 0°, must be provided for the freezer.

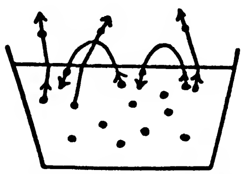
Pressure, too, results in a slight reduction of the freezing point. This fact is of practical significance. Ice skates glide easily over the surface, because the ice melts temporarily under the sharp runners,

and the water thus formed provides excellent lubrication. Snowballs stick together only because the pressure that is applied when they are formed melts the crystals at a few points of contact. When the pressure is released, the water refreezes and holds the particles of snow together. Perhaps you have noticed that it is almost impossible to form a snowball during very cold weather. The pressure of your hands is then insufficient to melt the snow crystals, and the snowball falls apart.

VI. *What Happens When Water Boils?*

Any open body of water, if left unreplenished, will evaporate and eventually disappear completely. Everyone knows that the evaporation takes place more rapidly at high temperature that at low temperature, and that boiling greatly speeds the process. But how much do you really know about the process we call boiling?

Let us consider first the matter of evaporation. With our knowledge of molecular behavior we can readily explain the known facts. Because of their heat energy, the molecules of a liquid are always in rapid motion. Some are moving faster than others, and a few have sufficient energy to jump right out of the surface and to escape completely from the attraction of the neighboring molecules. Now it may happen that many of these evaporated molecules will eventually find their way back to the surface and thus recondense. This is especially probable if the air is already saturated or nearly saturated with water vapor. But if the air is fairly dry and if there is some circulation of the air to carry off the moist layer near the surface of the water, then there is a continuous loss of molecules from water to air.

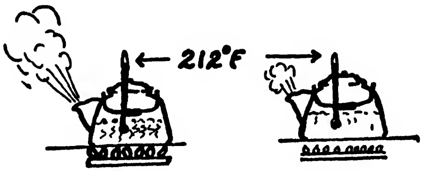


Evaporation. The fastest-moving molecules escape from the liquid surface.

It is easy to understand why warm water should evaporate more rapidly than cold water. The warm water contains a larger proportion of high-speed molecules with sufficient energy to tear themselves away from the surface. Or, we may look at the matter from

the standpoint of vapor pressure. Suppose that the liquid and its vapor are contained in a closed vessel; then evaporation will continue until molecules return to the surface as fast as they leave. The liquid is then in equilibrium with its vapor, and the space above the liquid is saturated with vapor. But the higher the temperature, the more molecules there will be in the vapor state. If we measure the concentration of vapor molecules by the pressure they create, we shall find that the vapor pressure becomes greater as the temperature is raised.

Every liquid, then, when it is in equilibrium with its vapor, has a definite vapor pressure; and this pressure increases with rising temperature. For example, at 20° C. the vapor pressure of water is 0.34 pounds per square inch. At 100° C. the vapor pressure of water is 14.7 pounds per square inch.



Vigorous boiling does not raise the temperature of the water; it only hastens evaporation.

This last figure is significant. It give us a hint about the true nature of the boiling process: 14.7 pounds per square inch is atmospheric pressure at sea level; but it is also exactly the vapor pressure of water at the boiling point. Evidently, *when the vapor pressure of a liquid becomes equal to atmospheric pressure, the liquid boils.* In other words, bubbles of steam appear,* and evaporation takes place not only from the surface but from the interior of the liquid as well.

Once a liquid is heated to the boiling point, its temperature can be raised no higher. The application of additional heat merely hastens the formation of steam bubbles, with the result that the liquid boils more vigorously and evaporates more rapidly. In other words, more molecules gain the necessary energy to escape. Since

* The bubbles of steam are not to be confused with air bubbles that appear at a temperature considerably below boiling. Heating drives out of solution the air that is normally dissolved in the water. Incidentally, real water vapor and steam are completely invisible. The white cloud that we see coming out of the tea kettle or out of the exhaust of a steam engine is actually made up of tiny water droplets. The steam has already recondensed.

the time required for cooking depends only on the temperature, water that is boiling vigorously will cook the vegetables not one whit faster than will water that is simmering or boiling gently. Many housewives and cooks do not know this. As a result, much food is scorched when the kettle boils dry and much fuel is wasted, because the cook is convinced that dinner will be ready sooner if the boiling proceeds at a rapid pace.

At pressures other than normal atmospheric, the boiling temperature is altered, because then a higher or lower temperature brings the vapor pressure of the liquid up to the pressure of the atmosphere. At the top of a mountain a mile high, where the barometer reads 26 inches instead of 30, water boils at only 95° C. (203° F.). On Pike's Peak (14,100 feet high) the boiling point is 86° C. (186° F.). Under such conditions, it takes a long time to boil an egg or to cook vegetables. Pressure cookers are therefore a great convenience at high altitudes. These cookers are sealed vessels in which the pressure, and hence the temperature of boiling, may be raised to any desired value, limited only by the bursting strength of the container. A safety valve permits escape of the steam when the pressure reaches a critical point.

Only the fastest-moving molecules are able to escape from a liquid surface. As a result, evaporation robs a liquid of part of its heat energy, and the liquid is cooled. Unless heat is provided from an external source, any evaporating body of water is cooler than the surrounding air. But the temperature difference is greatest when the available area for evaporation is made as large as possible, and when the air is circulated vigorously to carry away the saturated vapor. Porous water jars (*ollas*, for instance) and coolers covered with moist burlap are widely used in hot climates where ice is not available. Such devices are especially effective in the dry air of the desert; they are not nearly so satisfactory in a damp tropical climate where the humidity is high. For, in the tropics, the air is nearly saturated already with water vapor, and additional water evaporates very slowly.

When water evaporates and changes into vapor, its temperature remains constant, but it absorbs large quantities of heat—in fact, about 540 calories for each gram of water vaporized. With such a large heat of vaporization, no wonder it takes a long time to boil the kettle dry. Nor is it surprising that evaporation is very effective in keeping the surroundings cool.

This same 540 calories is, of course, given out when a gram of vapor is recondensed to water. For this reason, the condensation of a comparatively small quantity of steam in the radiators provides sufficient heat to keep your house warm even in the coldest weather. Evidently, too, for the sake of economy, a kettle should be kept covered when it is boiling. If the steam escapes into the atmosphere, the heat of vaporization is permanently lost. But if the steam recondenses inside the walls and lid, the heat is recovered and is available for heating the contents of the kettle.

VII. *Why Do Geysers Erupt?*

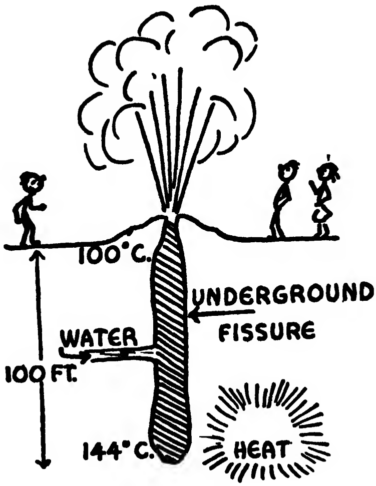
Of the many natural wonders that bring so many visitors to Yellowstone National Park, the geysers are among the greatest attractions. Old Faithful, in particular, draws a large audience at each regular hourly performance, when it ejects tons and tons of water and steam skyward to a height sometimes greater than 200 feet. Here we have a spectacular and seemingly mysterious natural phenomenon for which there should be some explanation.

As a matter of fact, our knowledge of heat, vapor pressure, and boiling will enable us to understand readily the behavior of the natural geysers. First, let us consider the shape of the underground fissure that supplies the geyser with water. There must be a long tubular crevice, which is fed at a comparatively slow rate by seepage water, and is heated by subterranean sources. Probably in most cases there is a bottleneck at the surface that tends to impede the flow during eruption.

As the geyser fills with water, the temperature at the bottom of the tube gradually rises to the boiling point. But, because of the pressure exerted by the long column of water extending above, boiling does not begin at 100° C. A higher temperature is needed. If, for example, the depth of water is 100 feet, the portion at the bottom must be raised to 144° before the vapor pressure is equal to the total pressure exerted by water plus atmosphere. Eventually, however, the necessary temperature is attained, and bubbles of steam begin to form at the bottom of the fissure. This forces water out of the top, with the result that the pressure at the bottom is immediately lowered. The reduction of pressure lowers, in turn, the boiling point —which means that water at the bottom is then well above boiling temperature. This state of affairs causes still more rapid boiling. In

fact, the water changes to steam with almost explosive violence, thus creating sufficient force to eject a stream of water high into the air.

The fact that some geysers, such as Old Faithful, erupt at regular intervals need not surprise us. If the supply of water is constant, a definite length of time is needed to fill the tube. A further period is required for heating the water to boiling. Thus, if the flow of



A geyser at the beginning of its eruption.

water and supply of heat are both uniform, the eruptions will occur on schedule. Otherwise, the geyser will perform irregularly.

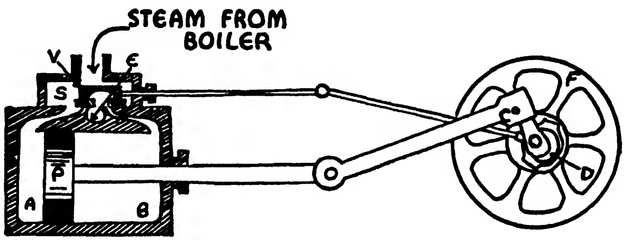
The above explanation of geyser action is not pure speculation. Though it is probable that no one has ever ventured to descend into a natural geyser for the purpose of investigating its action, artificial geysers, on a small scale, have been thoroughly studied in the laboratory.

VIII. *How Do Heat Engines Work?*

Despite the inroads made by electricity, heat engines still remain our greatest source of power. In fact, much of our electricity is itself generated by steam engines. Among the engines that transform heat energy into mechanical energy (and are therefore classed as heat engines) may be listed reciprocating steam engines, steam turbines, and internal combustion engines of the gasoline and Diesel types.

In all these cases, and in any heat engine, the chemical energy in the fuel is first changed to heat energy by burning, and a part of this heat energy is then changed into mechanical energy. Only a part—there is a definite limit to the fraction of the random motion of the molecules that can be changed into the ordered motion of pistons, cranks, wheels, and other mechanical devices.

A simple jet-type of steam engine was invented by Hero of Alexandria as early as the second century B.C. But the first practical engine was designed by Thomas Newcomen in the year 1710 for the purpose of pumping water out of the coal mines in England. Even Newcomen's engine was a pretty crude affair; and it remained for James Watt, some sixty years later, to make the vital improvements that finally enabled steam engines to replace horse- and man-power



The double-acting reciprocal steam engine. The piston *P* is driven by steam entering the cylinder *A* from the steam chest *S*. Exhaust steam is driven out of the cylinder *B* through the exhaust *E*. *C* is the chankshaft; *D* is an eccentric that controls the motion of the sliding valve *V*; *F* is the flywheel.

for so many industrial operations. Most of Watt's inventions such as the condenser and automatic valves remain even to this day as essential features of reciprocating steam engines.

No doubt you are familiar with the principle of the reciprocating steam engine. Steam, generated in a boiler under pressure, is admitted through the intake valve to a cylinder containing a sliding piston. Expansion of the steam pushes the piston to the far end of the cylinder. In the double-acting engine, the piston is driven on the return stroke by admission of steam to the other end of the cylinder. With the aid of a connecting rod and crankshaft, the to and fro motion of the piston is converted into rotation. A heavy flywheel is usually provided for the purpose of maintaining the speed constant during the time when the steam is not pushing on the piston. The intake and exhaust valves open and close at the appropriate

times to admit steam to the cylinder and to permit the escape of the spent steam.

The faithful old reciprocating engine was the world's principal source of mechanical power for over a hundred years. It is still used in railway engines, in many ships, and in some stationary installations.

In recent years, the steam turbine has replaced the reciprocating engine for some purposes, particularly in electric generating plants and in ships. The turbine is a sort of steam windmill. Jets of high-pressure steam play against hundreds of tiny fan blades located near the rim of an enclosed wheel, called the *rotor*. Some of the blades are several inches long; others are scarcely an inch in length. The rotor is driven at a high speed, often making 5,000 or more revolutions per minute.

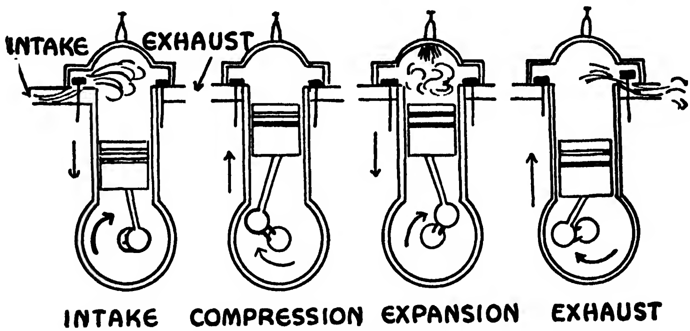
The chief advantages of the turbine are its freedom from vibration and its compactness. It delivers far more power than a reciprocating engine of equal size and weight. But in driving a ship, where the propeller may not exceed a speed of a few hundred revolutions per minute, the turbine must be geared down. The reduction gear is likely to give trouble, and in any case it wastes considerable power in friction. Some modern ships employ the steam turbine to drive a huge electric generator, which, in turn, provides current to drive an electric motor mounted directly on the propeller shaft. A turbo-electric drive of this type would seem to be unnecessarily complicated and cumbersome. In practice, however, its efficiency is actually higher than the turbine and reduction-gear combination. But the greatest advantage of the turbo-electric drive lies in its flexibility. In maneuvering a ship, the speed of the electric motor can be readily changed, and the propeller can be quickly put into reverse. Maneuverability is especially valuable in the case of warships, where the turbo-electric installations are meeting with increasing favor. Turbo-electric (and Diesel-electric) drives are also helping to speed up railway service and to reduce the cost of transportation. Gradually these speedier installations are replacing the picturesque locomotive, with its puffing, snorting reciprocating engine.

Nowadays, with nearly 30 million automobiles on the highways of the United States alone, gasoline engines far outnumber any other type of heat engine. The chief advantages of the gasoline engine are compactness, efficiency, comparative simplicity, and ease and quick-

ness of starting. The fact that it may be made nearly fool-proof in the hands of an inexperienced operator is also an important point in its favor.

Perhaps you never thought of the gasoline engine as a heat engine. You know, of course, that an explosion of a mixture of gasoline vapor and air provides the driving force on the piston. But this explosion does not produce a high pressure by creating an excess of gaseous material. Instead, the pressure is produced principally by the high temperature of combustion.

When the pressure of the air around a gasoline engine is reduced, less of the mixture of gasoline vapor and air is forced into the cylinder in each cycle, and the power developed by the engine is correspondingly lowered. To overcome this difficulty, military aeroplanes



The four cycles in the cylinder of a gasoline engine.

operating at high altitudes are equipped with superchargers which compress the rarefied air and thus crowd a large quantity of the inflammable mixture into the cylinders on each intake stroke. Some of these superchargers are driven by gears from the engine; others are driven by a turbine which is turned by the hot exhaust gases from the engine. The ability to reach a high altitude and to maneuver there is very important for warplanes, and the outcome of an aerial engagement is often determined chiefly by this factor.

The engine in your automobile is of the 4-cycle type. There are also 2-cycle internal combustion engines, but they are not very common. The term *4-cycle* refers to the fact that, out of four strokes (two up and two down) of the piston in any one cylinder, only one stroke delivers power. In other words, each cylinder fires once dur-

ing every two revolutions of the crankshaft. In a 6-cylinder engine, one or more of the cylinders is furnishing power at all times, because a power stroke begins each third of a revolution of the motor, and continues throughout the ensuing half revolution. Before the power stroke of one cylinder ends, that of another cylinder begins. For this reason, an engine containing six or more cylinders runs with less vibration than does one with fewer cylinders.

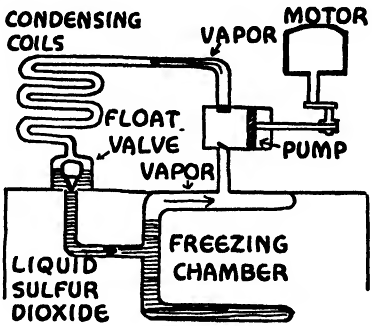
The Diesel engine is quite like the gasoline engine, except that its compression ratio is so high (16 to 1) that no electric spark is needed to ignite the mixture. Air alone is compressed initially in the cylinder. The fuel is injected just as the piston reaches the top of the compression stroke; and the temperature of compression is so high that combustion starts spontaneously. Chiefly because of its high compression ratio, the Diesel engine is more efficient than the gasoline engine. It also burns lower-priced fuel. Diesels are used extensively in ships, streamlined trains, tractors, and even motor trucks. So far, it has not been possible to manufacture small, light-weight Diesels cheaply enough for use in automobiles.

A word about the efficiency of heat engines: In general, the higher the initial temperature and pressure of the heated vapor (whether the vapor be steam or burned fuel) and the lower the final exhaust temperature and pressure, the higher will be the efficiency—that is, more of the heat energy contained in the gas will be utilized. For this reason, high-compression gasoline engines are more efficient than low-compression engines. With the fuel available at present, the compression ratio is limited to a maximum of about 6½ or 7 to 1. At higher pressure, "pinging" or knocking becomes serious, and there is danger of spontaneous combustion of the mixture due to compression heating.

In spite of all efforts at improvement, the efficiency of heat engines remains low. The theoretical maximum is limited by the initial and final temperatures of the hot vapor. In practice, the theoretical efficiency is always far below 100 per cent. But even the theoretical efficiency is by no means realized. Friction, imperfect combustion, and heat losses take a heavy toll. Locomotives and small stationary steam engines seldom convert as much as 10 per cent of the heat energy contained in the fuel into mechanical power. Large steam engines and automobile engines have efficiencies up to 25 per cent; Diesels, as high as 35 per cent.

IX. *How Do Mechanical Refrigerators Work?*

In these days when nearly every modern home is equipped with an electric or a gas refrigerator, no discussion of heat and cold would be complete without a description of these devices. But you should realize right at the start that a mechanical refrigerator does not manufacture cold. It merely takes heat away from one region (the interior of the refrigerator) and deposits it in another region (the outside air). An electric refrigerator actually warms the room in which it is operating. This is true even if the door of the refrigerator is left open. For, the electric energy that drives the motor is eventually transformed into heat (through friction) and the heat energy thus created is liberated in the room. The operation of the refrigerator causes no other net transfer of heat into, or out of, the room.



The essentials of an electric refrigerator. Evaporation of liquid sulfur dioxide cools the freezing chamber.

Mechanical refrigerators depend for their cooling effect on the evaporation of a liquid. There is no mysterious behavior of the electricity that accounts for the refrigeration. The current merely drives a motor that starts automatically with the aid of a thermostat when the temperature inside the refrigerator rises higher than a certain set point. The motor operates a circulating pump.

The liquid refrigerant is either sulfur dioxide or some other material that evaporates readily and can be reliquefied under moderate pressure. A supply of liquid, contained in the freezing chamber inside the refrigerator, evaporates rapidly when the pump starts up and the pressure is reduced. The large quantity of heat required to vaporize the liquid (the heat of vaporization) is withdrawn from the metal chamber, which thus becomes very cold. The vapor removed

from the freezing chamber is recondensed by the pump and once more turns to liquid in the condensing coils, which are placed outside of the refrigerator. The heat liberated by condensation is dissipated to the surrounding air. When sufficient recondensed liquid gathers in the coils, a float-valve opens, allowing the cooled liquid to flow back into the freezing chamber. There, the cycle starts all over again. A continuous circulation of the refrigerant thus serves to transfer heat from the interior of the refrigerator to the outside. That is all there is, in principle, to any mechanical refrigerator.

Large commercial refrigerating plants operate much like the electric refrigerators that we have in our homes—except that the refrigerant is usually ammonia instead of sulfur dioxide. Ammonia is employed also as the refrigerant in the popular gas-operated home refrigerators. The cyclic process in these gas devices is somewhat more complicated than in the electric refrigerators; but no moving parts are required. A small gas flame drives the ammonia gas out of an absorption chamber, which contains a strong solution of ammonia in water. The ammonia gas is condensed into liquid ammonia by air or water cooling, and after evaporating in the refrigerating chamber, is eventually reabsorbed in the water where it is ready to begin a new cycle.

The gas-operated refrigerator is a clever invention. But there is nothing essentially mysterious or even remarkable about producing cold with the aid of heat. In an electric refrigerator, the refrigerant is circulated (that is, it is evaporated and recondensed) by a mechanical pump. In the gas refrigerator, the same circulation is accomplished by a different kind of agency; namely, heat energy in the form of a gas flame. In any case, energy must be supplied when heat is transferred from the cold inside to the warmer outside of the refrigerator.

CHAPTER TEN

ABOUT THE WEATHER

I. *What Is Meteorology?*

One might think that meteorology would have something to do with the study of meteors or "shooting stars." But such is not the case. The science of meteorology deals instead with climate, weather, and weather forecasting. It is a physical science, because physical conditions in the atmosphere determine the kind of weather that we are going to have. No scientist believes that the "sign of the moon" or portents of an astrological nature have anything to do with the weather.

On the other hand, many of the ancient adages, such as,

> Red sky at night is the sailor's delight;
> Red sky in the morning is the sailor's warning,

do have some foundation in fact. Their predictions are at least based on physical atmospheric phenomena. Likewise, the local seers who tell us that we are going to have rain tomorrow because of "that feel in the air" are often right—as are the oldsters who "feel in their bones" that a storm is coming. Rheumatism seems to be associated with atmospheric conditions that frequently presage a storm.

The local prophets may not be as accurate as the Government Weather Bureau; but if they confine their predictions to a day or so in the future, they may do very well in their own locality. On the other hand, the old-timer who claims that he can forecast for weeks or months ahead is simply deluding everyone—very often himself included. Sometimes, as a result of lucky guesses, such men attain considerable fame for a time. People seem to remember the correct guesses and forget the wrong ones. Although some progress is being made on scientific long-range forecasting, at present there is no accepted method of predicting weather in detail for more than a few days ahead and the forecast is usually based on widespread knowledge of conditions in other areas. Even then, conditions may change suddenly, and the best of predictions will go astray.

Obviously, the day-by-day forecasts for a year ahead that appear on almanacs and calendars are out and out guesses. Even if there were some basis for predicting weather so far ahead, it is ridiculous for an almanac, distributed over a large area, to forecast local conditions. The weather varies too much from one region to another.

In the recent war there were many instances where the success or failure of a military enterprise was determined largely by the weather. The government ban on radio broadcasting of weather forecasts and conditions, and the sketchiness of the weather information available in the newspapers, continually reminded us that a

Rain or shine? The local seer often predicts correctly.

knowledge of what the elements were about to do was an important military secret. Even the almanacs and calendars no longer carried their customary display of predictions—though we can regard this particular reticence as no more than a gesture to show the proper patriotic spirit.

With the lives of many people depending on accurate knowledge of the weather conditions along commercial airlines, and with the fate of nations, perhaps, depending on the weather during a military operation in wartime, it is not surprising that the science of metorology is becoming more and more important every day. Later, we shall catch a glimpse of the forecasting methods used by the meteorologists. But first, we must discuss the conditions in the atmosphere that cause wind, fog, rain, snow, thunderstorms, and other weather phenomena. Then we shall be able to understand how these disturbances can be predicted.

II. *When Do We Feel Hot, and When Cold?*

If there is nothing else to talk about, the weather always serves as a topic for conversation. Despite the jokes about weather-talk, most of us are genuinely interested in the state of the weather—at least, as it affects our own bodily comfort and discomfort. Is it going to be hot or cold? wet or dry? We want to know.

As a matter of fact, just when do we feel hot, and when do we feel cold? This question cannot be answered easily. The temperature of the air is, of course, an important factor—probably the most important. But other factors must be considered, too. Why is it that in winter people sometimes complain of feeling chilly in a house heated to 80° F.? On the other hand, in many regions, a summer temperature of 80° is oppressive; 90° is stifling. But on the desert, 90°—even 100°—is by no means unbearable.

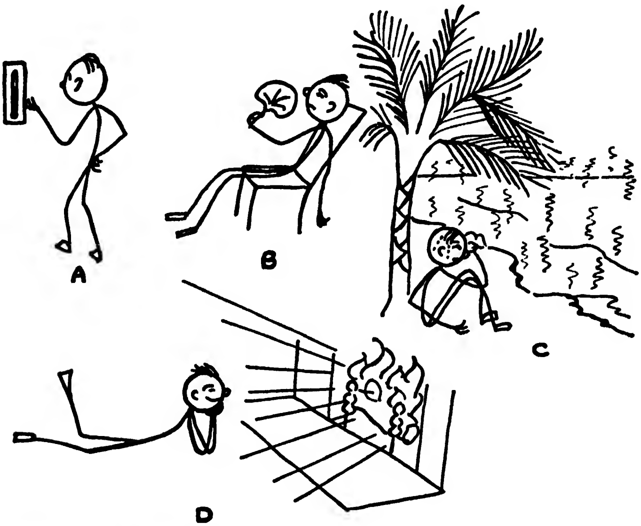
To a great extent, these seeming paradoxes are caused by the varying rates at which we are able to evaporate water from our bodies. When the temperature is high, we feel cool, or at least comfortable, if our perspiration evaporates speedily. Our bodies then act like a burlap-covered cooler or a porous water jar: the heat of vaporization, being withdrawn from our bodies, effectively cools them. On the other hand, if our sweat evaporates slowly, we feel uncomfortable in hot weather.

The question next arises: What determines the rate of evaporation from our bodies? Obviously, free circulation of air helps. A breeze, if unhindered by heavy clothing, carries away the saturated layer of air next to our skin and thus makes it possible for more water to evaporate. An electric fan helps for this reason. But even a fan does little good on a damp, "muggy" day. This is because another factor, humidity, is important in determining the rate of evaporation. If the humidity is high—that is, if the air already contains nearly as much water vapor as it can hold—the rate of evaporation must obviously be slow. That is the reason why we are so uncomfortable in the damp tropical heat of summer. In winter, however, the humidity is low, especially in a heated house; and at 80° our bodies may evaporate moisture so rapidly that we actually feel chilly.

When you read the weather report in the newspaper, you find the humidity expressed as a number—say, 30, 50, or 80—always less than 100. This number refers to the per cent *relative humidity;* that is, to the ratio (expressed in per cent) of the water vapor actually contained in the air, to the quantity contained in saturated air at the

temperature in question. As we saw in the last chapter, the total water content of saturated air increases as the temperature is raised; but it is the relative humidity and not the total water content that determines the rate of evaporation—and hence determines bodily comfort.

Obviously, from the above definition, a relative humidity of zero would mean that the air was perfectly dry; while a relative humidity of 100 would mean complete saturation. Except in the stratosphere, 10 miles or so above the surface of the earth, the humidity is never



Four factors affecting bodily comfort. (*A*) Temperature. (*B*) Circulation of the air. (*C*) Relative humidity. (*D*) Radiation.

zero. But on the desert it is low—perhaps 20 or 30 per cent. Your own house in winter is likely to be as dry as the desert unless special precautions are taken to evaporate extra moisture into the heated air. When the humidity falls below 40 or 50 per cent, we are uncomfortable because our skin feels dry and tends to become chapped. The low humidity does help, however, to keep us cool in hot weather.

In many regions, the summer humidity rises because of increased evaporation from oceans, lakes, trees, and ground, until it frequently reaches 80 or 90 per cent. During a rain, the humidity is nearly 100 per cent. Generally speaking, a temperature higher than 80°, accompanied by humidity of more than 80 per cent, results in acute

discomfort, because our bodies are unable to evaporate sufficient moisture to keep us cool.

Besides temperature, wind, and humidity, there is at least one other factor that determines whether we feel hot or cold. This factor is radiation. The sun's rays or the heat from a stove help us to keep warm (even make us uncomfortably hot) when the air itself is cool. Thus we feel warm in the sun when the thermometer reads 50° or less in the shade. Radiation from a stove or fireplace will keep us comfortably warm in the house, when the air is at a temperature of 60° or less. But on a hot summer day, we avoid the sunshine, because it adds to our discomfort.

To sum up, then: at least four factors affect our sense of well-being in respect to heat and cold. These are *temperature*, *wind*, *humidity*, and *radiation*. Though we can adapt ourselves to a wide variety of conditions, it is safe to say that most of us feel most comfortable when we are in the shade, with a gentle breeze blowing, with the temperature between 70° and 75° F., and with the relative humidity in the neighborhood of 50 per cent. But in a dry climate, 80° may be quite comfortable; and when we are exerting muscular effort or we are wearing heavy clothes, a temperature below 70° is better. Sitting still in a room at about 65° for any length of time without added clothing is insidiously dangerous as our temperature reduces imperceptibly to a point where the resistance to infection is lowered. If temperatures are lower the cooling is such that we react by shivering and act to protect ourselves.

III. *How Is Air Conditioning Accomplished?*

Since we seldom enjoy ideal weather conditions, the next best thing is to manufacture our own weather. Air conditioning makes this possible inside of closed buildings. Complete air conditioning includes heating the air when it is too cold, cooling the air when it is too hot, humidifying the air when it is too dry, drying the air when it is too humid—as well as circulating the air and removing dust from it. If all of these things are done adequately, there is nothing to be gained by continuously supplying much fresh air from the outside. The same air may be recirculated a number of times. This constitutes a distinct saving, because the air drawn from inside the building is already partially conditioned and nearly at the desired temperature.

Only in recent years have complete air-conditioning units been available. We have always done part of the job. A stove, a fireplace, or a furnace is an elementary sort of air-conditioning apparatus, because it warms the air if it does nothing else. But most heating devices of this kind make the humidity conditions worse instead of better. The cold air contains very little moisture to start with. Heating does not remove water vapor, but it does greatly reduce the relative humidity—often, as we noted earlier, to values as low as 20 or 30 per cent. Such low humidity causes our furniture to dry out, crack, and come apart at the joints. It also causes our skin to become dry and leathery, with the result that we are sometimes afflicted with a troublesome winter itch. Some authorities believe that the hot, dry air in our houses during the winter is partly responsible for the prevalence of colds, grippe, and pneumonia.

The problem of humidifying dry air is not a simple one. It is particularly difficult with a steam or hot-water heating system. Most hot-air furnaces are equipped with pans for evaporating water; but in the majority of cases these are entirely inadequate—if, indeed, the furnace tender ever remembers to fill them with water. Normally, in an average-sized home, several gallons of water must be evaporated each day in order to maintain a satisfactory humidity—say 40 or 50 per cent. Few of the older hot-air furnaces evaporate anywhere near that much. Steam and hot-water radiators supply little or no moisture to the air.

The modern hot-air heating system contains a blower that forces air through a filter consisting of a fine spray of water, a damp cloth, or some equivalent device. A filter of this kind not only removes dust, but humidifies the air at the same time.

Summer air conditioning in the desert is relatively simple. Here the air is initially too dry and one needs only to blow a current of air through a wet filter, thus cooling and humidifying in one operation. In most sections of the United States, however, this scheme will not work, because the air is already too wet, and it must therefore be dried as well as cooled. The drying is often accomplished by blowing a stream of air through a spray of very cold water. The water is so cold that moisture condenses out of the air onto the droplets. Thus we have a paradoxical situation in which humidity is actually reduced by bringing air into contact with water.

The power required to cool the summer air is surprisingly great. On the average, it takes as much power to cool a building 20° or 25°

below the temperature of the outside air as to heat it 60° or 70° in winter. This difference is largely explained by the heating effect of people, stoves, lights, and the sun's radiation. Such sources of heat help to keep the building warm in winter; but they necessitate additional cooling in summer. Most air-conditioning systems use electric refrigeration in one form or another. This is satisfactory, but is, of course, rather expensive in most localities, when you remember that the cost of cooling the summer air is comparable with the cost of heating by electricity in the winter.

For this reason, and also because of the initial expense of buying the equipment, summer air conditioning of private homes may be considered a luxury. But many theatres, restaurants, and stores find that, in spite of the high cost, air-conditioning pays for itself in increased patronage. Office buildings are being air-conditioned in increasing numbers—not only for the sake of comfort, but because the higher working efficiency of the employees warrants the expense.

Everyone likes to be comfortable. Therefore, the great majority of people seem to approve heartily of air conditioning. There is still a suspicion, however, that the sudden and frequent climatic changes experienced by persons going in and out of air-conditioned buildings may make them more susceptible to colds. The medical evidence for or against this belief is not yet clear, and meanwhile most people are willing to take the certain benefits of comfort, even if they may be accompanied by a small danger of harm.

IV. *What Causes General Atmospheric Circulation?*

Outside of air-conditioned buildings, we are obliged to take the weather as it comes. It behooves us, therefore, to study the causes of weather and of weather changes so that we may be prepared to meet the rigors of our respective climates. Wind is perhaps the greatest single factor in controlling weather and climate. Let us, therefore, begin our study of scientific meteorology by investigating the causes and effects of winds.

All winds, from the tiniest gust to the great trade winds that blow steadily over a considerable portion of the earth, owe their origin to convection currents. Warm light air rises in accordance with Archimedes' Principle, and the heavier cold air rushes in behind to take its place; or heavy air falls and pushes aside the neighboring light air. In any case, the horizontal winds that we encounter on the surface of the earth always result from updrafts or downdrafts

somewhere. Generally speaking, air rises because it becomes heated by the sun's rays or contact with surfaces warmed by the sun, and expands. In other words, it absorbs more radiation from the sun and earth than it emits. On the other hand, air falls because it is colder and more dense than a neighboring region of warm air. Therefore, unequal heating of the earth's surface by radiation of the sun is always an essential, or at least a contributing, factor in atmospheric circulation.

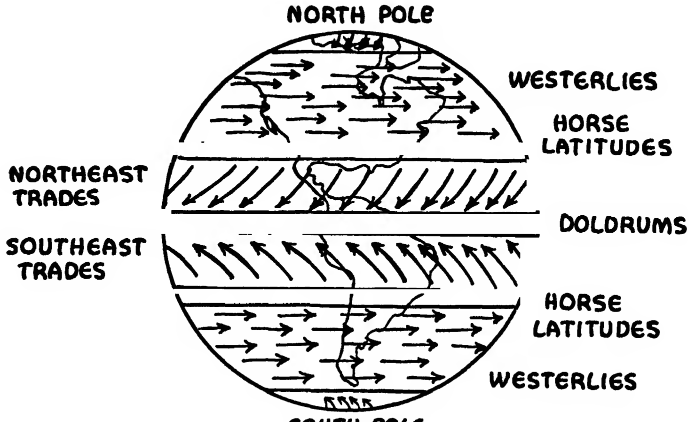
The heat of the sun is not, however, the only factor in determining the motion of the atmosphere. For example, humid air tends to rise above neighboring bodies of dry air. This is explained by the fact that water vapor is only about 2/3 as dense as dry air. Air containing a large proportion of moisture is thus comparatively light. Furthermore, the direction and strength of the winds are profoundly altered by the rotation of the earth, as well as by such factors as the deflecting and frictional effects of mountains and whole continents.

The complete story of the origin and maintenance of winds is extremely complicated and some phases of it are not fully understood. But we can account for some of the common types of winds easily enough. The most widespread flow of air over the surface of the earth is caused by unequal heating of the polar and equatorial regions. Because it receives more radiation from the sun, the air at the equator is always warmer than the air at the poles. Hence, we might expect that there would be upward convection at the equator and a downward flow near the poles. These movements would, in turn, cause a general horizontal flow over the surface of the earth from poles to equator, with a corresponding return flow at high altitudes from the equator to the poles. In other words, we in the northern hemisphere might expect continued cold north winds blowing down on us from the arctic regions; while the southern hemisphere would experience equivalent south winds originating in the antarctic.

As a matter of fact, the prevailing winds in the northern hemisphere do, on the average, blow somewhat from north to south; while those in the southern hemisphere have a similar component from south to north. But very often, in the temperate regions, the winds are warm and not cold, for the simple reason that the circulating air never reaches the cold poles. Instead, the warm tropical air from the equator sinks to the earth and starts its return flow to the south

before it ever becomes very cold. Hence, it is only occasionally in the temperate zones that we experience a real icy "norther."

Furthermore, because of the rotation of the earth, our prevailing winds (in the northern hemisphere) can scarcely be called north winds. Actually, in the temperate zone, they are much more nearly from the west; while the trade winds near the equator blow in the opposite direction; that is, from the east (actually, the northeast). We cannot discuss in detail the reasons for this effect of the earth's rotation. But, in brief, mechanical principles require that a wind, blowing initially from the equator to the north pole, should be de-



The prevailing winds on the earth.

flected to the right (that is, toward the east); while the return undercurrent would have a compensating westward component. This prediction is, in fact, verified by measurements of the wind direction and velocity all over the surface of the earth.

If we were to start on a trip northward from the equator, we might expect to find the following average wind conditions (greatly modified by local storms and neighboring continents): For the first two or three hundred miles we should be in the *doldrums*, a region of comparative calm, where the trade winds coming down from the northern hemisphere meet those from the southern hemisphere. Next, we should pass through some 1,500 to 2,000 miles of more or less steady, gentle (10 to 15 miles per hour) trade winds, blowing from the northeast. The trade winds extend as far as 30° north—about to the southern part of the United States.

For the next few hundred miles, we might expect to encounter fitful, variable winds, often calms of long duration. This region is known as the *horse latitudes,* reputedly because, many years ago, the sailing ships carrying horses from England often found it necessary to dump part of their cargo of horses overboard, when supplies of food and water became depleted during the long periods of calm.

Still farther north, we should find the prevailing west winds that are characteristic of the temperate zone. Across most of the United States, for instance, the wind blows more frequently from the west than from the east. Near the north pole, because of the settling of the cold air, the wind blows rather steadily from the north.

Corresponding circulation of this same general type is found in the southern hemisphere.

V. *What Is the Origin of Local Winds?*

The general wind conditions just described are strictly average distributions. On any particular trip from the equator to the north pole, you would very likely encounter something quite different. As we noted earlier, local disturbances—storms, irregular heating, surface friction, and the like—are almost always present. In fact, some of these "local disturbances" cover a huge expanse and are of common, even regular occurrence.

Daily land and sea breezes, for instance, are regularly encountered near the seashore. During the dry summer forenoons, the land surface is heated more rapidly than the water.* The hot air over the land thus rises during the late forenoon and early afternoon, and is replaced by cool air drawn in from over the ocean. These sea breezes usually do not extend more than a few miles inland, but they are very effective in maintaining a cool, equable climate on a narrow strip of land bordering the ocean. This is the chief reason why the California seacoast is famous for its comfortable summer climate. The hot, arid interior is ideal for the formation of strong sea breezes that cool the coastal plains during the day.

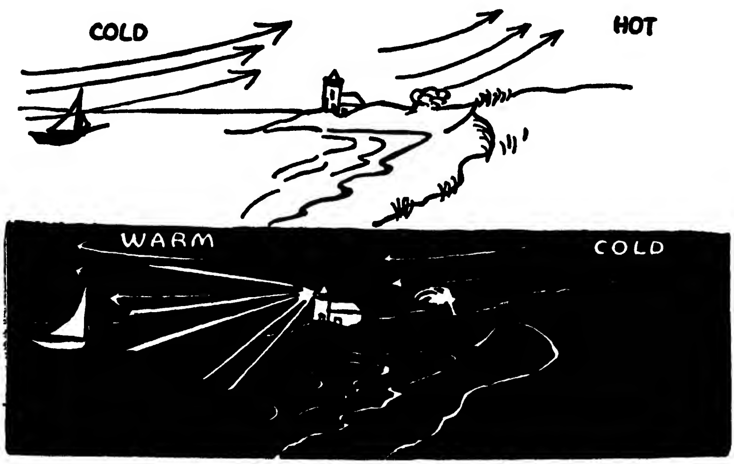
At night, near the ocean, the situation is reversed. The water retains its heat, while the land cools rapidly by radiation. As a

* This difference between land and water in the rate of heating (or cooling) is attributed to a number of causes: evaporation helps to keep the water cooler than the land; the high specific heat of water results in slower change of temperature; water is a poorer absorber (and emitter) of radiation than the land; the heat absorbed by the water penetrates to a greater depth.

result, a land breeze, usually more gentle than the daytime sea breeze, commonly blows out to sea during the night.

Winds essentially similar to land and sea breezes are encountered in many places. They are common around large lakes and even near green, damp forests. The sides of mountains are often strongly heated during the daytime, with the result that *valley breezes* blow up the mountain; while the reverse *mountain breezes* blow down into the valleys at night.

Whenever cold, high mountains or plateaus are adjacent to warmer, lower bodies of water, there is a drainage of cold air down



The sea breeze blows in the daytime, and the land breeze blows at night.

the slopes joining the two regions. The greater the difference in level and the greater the difference in temperature, the stronger are the winds. The high glaciers covering most of Greenland, and the ice cap on the Antarctic Continent, for instance, give rise to more or less continual *fallwinds* of this type. Often the icy wind attains gale-like velocities—50 or 100 miles per hour.

Some of these cascades of cold air flowing down from the highlands are so famous that they have been given names. The *bora* of the Adriatic Sea, and the *mistral* blowing down the Rhone Valley are examples. In the United States, continental fallwinds are either absent or very weak, because the highlands are comparatively warm and the slopes to the sea are gentle.

In some regions, the land and sea breezes persist more or less regularly for whole seasons, and cover a region extending far inland and far out to sea. Such winds are called *monsoons*. They are naturally most pronounced where the temperature difference between land and sea is greatest. The monsoons of India are the most famous; though similar winds occur in China, Africa, Australia, and even in the United States, particularly in the eastern region and in Texas. In every case, these seasonal winds blow in off the ocean when the land is heated during the summer, and blow in the reverse direction (from land to sea) when the land is cooled during the winter. However, the great extent of the monsoons makes them subject to the deflecting force of the earth's rotation. Consequently, they are directed obliquely to the shoreline, and not at right angles. On the Atlantic Coast of the United States, for instance, they blow from the southeast in summer and from the northeast in winter.

The winds so far discussed blow more or less in straight lines, or at least in very gradual curves. There is, however, an important class of winds in which the air gyrates in a spiral path, moving either inward toward the center or outward, depending on the circumstances. These spiral winds range in size from tiny whirlwinds a few feet in diameter, to giant cyclones and anticyclones that sometimes cover whole continents or oceans. They vary in intensity from the gentle zephyrs of the good-weather anticyclones, to violent hurricanes and tornadoes with their accompanying storms and destruction.

Let us consider first the small whirlwind of the type so common during hot summer days on the dry fields and plains of the United States. These whirls are usually no more than a few feet in diameter, extend to a height varying from a few feet to a few hundred feet, and normally do no particular damage—though they do pick up loose leaves and dust and sometimes scatter loose haystacks. The whirlwinds travel with the breeze, and may last for minutes or hours if the conditions are favorable. Like so many winds, they are caused by a rising current of warm air. The uniformly heated layer near the earth breaks through into the colder upper atmosphere at some spot, and the chimney-like action of this rising column produces a violent updraft. Air, rushing in from the sides to replace the rising stream, usually will not come in uniformly from all sides; it thus sets the column to whirling rapidly about its axis. The rotating

fluid moves in a spiral path upward and toward the center of the whirling column.

Tornadoes and waterspouts are also whirlwinds, which are larger in scope as they originate high in the clouds rather than on the ground and cover a larger area. There is no essential difference between a tornado and a waterspout, except that the tornado occurs on land and the waterspout at sea. They are the most violent of all winds, with the spiraling air revolving at a speed of 100 to 500 miles per hour and sweeping everything before it. Tornadoes revolve in

The tornado. In the northern hemisphere, the whirling funnel of air rotates counterclockwise.

the counterclockwise direction (in the northern hemisphere), and usually travel toward the northeast at a speed of about 25 miles per hour. They are always accompanied by a thunderstorm. Fortunately, the funnel-shaped "twister" seldom has a diameter greater than a quarter of a mile (often much less); and, many times, the whirling mass of air never reaches the ground, or else travels along the surface for only a short distance.

The last great classes of winds that we should mention here are *cyclones* and *anticyclones*. Since the cyclones, with their low-pressure areas at the center, are the chief source of winter rain and snow in the temperate zones, we shall be concerned with this type of storm again later on. Cyclone-winds spiral inward toward a rising column of warm air at the center. In this way, they are much like the small whirlwinds that we have just talked about. The cyclones, however, cover tremendous areas, often having diameters of 1,000 to 2,000 miles. The wind intensity varies all the way from gentle breezes to the terrific hurricanes of the West Indies and South Pacific and the typhoons of the West Pacific.

In general, the tropical cyclones are more violent than those we experience in the middle latitudes. They are also accompanied by heavier rain. In both tropical and extratropical cyclones, the wind revolves in a counterclockwise direction in the northern hemisphere (clockwise in the southern hemisphere) as a result of the earth's rotation. The rising column of warm, damp air at the center not only constitutes a low pressure area, but is usually a region of comparative calm.

Cyclones retain their identity for days at a time, and drift with the prevailing winds, usually at the rate of 20 to 30 miles per hour. Tropical cyclones move with the tradewinds in a westerly direction; the extratropical cyclones travel toward the east. A few cyclones are stationary and semipermanent. Such are the winter Aleutian "low" in the north Pacific and the Icelandic "low" of the north Atlantic.

The cause of cyclones is complicated and is none too well understood. Tropical cyclones originate in the doldrums, where strong convection is a common occurrence. The extratropical cyclones of the middle latitudes usually originate at a boundary between cold and warm masses of air. Many of them start at or near the semipermanent "lows," subsequently migrating away, as it were, from their parent cyclone.

Anticyclones are just the reverse of cyclones. They are characterized by a high-pressure area at the center. The wind spirals outward in a clockwise direction (counterclockwise in the southern hemisphere). Since the high-pressure central area is a region where cold air is falling toward the earth, the anticyclone is normally accompanied by clear, cold weather. In the middle latitudes, an anticyclone always follows after a cyclone—thus sweeps across the United States from west to east. The origin of some anticyclones can be traced directly to the cooling of the atmosphere by radiation. But, like the complementary cyclone that travels ahead, the anticyclone remains in some respects a meteorological mystery.

VI. *What Is the Cause of Dew and Frost?*

Having discussed the winds that are such an important aspect of the weather, we must now learn something about the conditions of temperature and humidity that cause condensation of moisture. Then, the connection between wind and rain will follow logically.

Condensation is, of course, the reverse of evaporation. So, recall, if you will, a few of the things that we have learned about

evaporation and humidity: Water continues to evaporate only until the air above becomes saturated. The quantity of moisture contained in the air at saturation becomes greater as the temperature is raised; but at saturation, the relative humidity is always, by definition, 100 per cent. Thus it becomes evident that whenever the temperature of a saturated vapor is lowered some of the moisture must condense out; hence, for example, the "steam" (actually, condensed droplets) coming out of the tea kettle spout, and the condensation of your breath on a cold day. If such condensation did not occur, the humidity at the lower temperature would exceed 100 per cent.

If the air is not saturated with water vapor (that is, if the relative humidity is below 100 per cent), the temperature can drop to some extent without any condensation. But eventually, as the temperature continues to fall, the saturation point will be reached. A further drop will result in part of the moisture condensing out. The temperature at which condensation begins is called, appropriately enough, the *dew point.*

The dew point varies, of course, with the total quantity of moisture contained in the air: when the air is very humid, the dew point is high; when the air is very dry, the dew point is low. But whenever the temperature of the air itself, or of any object located in the air, falls below the dew point, moisture must condense out in one of the familiar forms that we call dew, frost, fog, clouds, rain, snow, or the like.

This explains the "sweating," during the summer, of cold water pipes and of glasses containing cold drinks. The humidity is high, and the water pipes are frequently at a temperature lower than the dew point. Water thus condenses out of the air and forms droplets on the pipes.

It explains, too, the formation of dew and frost. First of all, you must realize that dew and frost do not actually *fall,* despite what the poets say. During clear, cool nights, the ground loses so much heat by radiation that its temperature frequently drops below the dew point. Therefore, moisture condenses on the leaves, rocks, and other cold objects available. Normally, frost is not frozen dew: the moisture is simply deposited as particles of ice when the temperature is below freezing.

Perhaps you have noticed that dew and frost seldom form on cloudy nights. This is explained by the blanketing effect of the clouds. The earth is maintained at a temperature above the dew

point, because radiation cannot escape into space. Instead, the radiation from the ground is largely returned to the earth by reflection (or by absorption and reemission) from the water particles in the clouds. In the way that it traps heat radiation, the cloud layer acts much like the glass of a greenhouse. For the same reason, dew and frost seldom form on the lower side of leaves and blades of grass. The space between the ground and the leaves is slightly warmed by radiation reflected back and forth.

Wind usually prevents the formation of dew or frost, because circulation of the air tends to maintain the surface of the ground and the adjoining layer of air at the same temperature as the main body of the atmosphere. In still air, the temperature of the ground is much more likely to drop below the dew point.

VII. *What Is the Cause of Fog, Clouds, Rain, and Snow?*

The heat of the sun is continuously evaporating huge quantities of water from oceans, lakes, vegetation, and damp ground. One might expect, therefore, that the atmosphere would always be in a state approaching saturation. But, fortunately for our comfort, vertical convection and the resulting horizontal winds instigate so much precipitation in local areas that the atmosphere as a whole never approaches 100 per cent relative humidity. In the temperate zones, the humidity is likely to average 50 per cent or less.

Whenever the temperature of a large region of the atmosphere falls below the dew point, there can be only one result: condensation of a portion of the water vapor. This condensation, initially, at least, takes the form of fog or clouds, with hundreds of tiny droplets filling each cubic centimeter of air. Subsequently, under favorable conditions, larger droplets or icy particles—rain, snow, sleet, or hail—may form.

There is no essential difference between fog and clouds, except that fog lies close to the ground, while clouds form at altitudes varying from a few hundred or a few thousand feet in the case of the low-lying *stratus* clouds, to heights of 5 or 10 miles (thus, even into the base of the stratosphere) in the case of the thin, wispy *cirrus* forms. These high cirrus clouds nearly always consist of frozen particles of ice. The thick, formless rain clouds (*nimbus* type) normally lie a mile or two above the surface of the earth—as do the towering thunderheads (cumulo-nimbus clouds) characteristic of thunderstorms. The tops of the tall thunderheads, however, are sometimes 4 or 5 miles above the ground.

Though all fogs and clouds are the direct result of condensation when a portion of the atmosphere becomes colder than the dew point, there are many causes for the necessary drop in temperature. Humid, low-lying air in the neighborhood of rivers, marshes and even valleys, often loses so much heat by radiation during a clear night that the temperature drops below the dew point. The fog thus formed is called *radiation fog*. Other fogs, also some clouds, are caused by the mixing of a body of warm, humid air with a body of cold air.

The great majority of clouds, however, are formed, not by mixing cold and warm air, but by the upward motion of heated air masses. As the warm air rises into the rarefied upper regions, it expands and therefore becomes cool. Soon, the dew point is reached, and condensation begins.

The cause of the upward motion is either local heating by the rays of the sun, or the interaction of warm and cold air masses; but the rise is sometimes aided by the topography of the land. Thus, the rainfall is likely to be greater on the windward side (the west in the United States) than on the leeside of mountain ranges. As the wind blows up the mountains, it cools and thus precipitates most of its moisture, with the result that there is little water left by the time the air blows down the leeward side. This is partly, at least, the cause of many of the world's large deserts, including the Mojave and the neighboring arid regions in the western United States.

With regard to clouds, the first question that might come into your mind is this: Why is it that the droplets in a cloud do not fall to earth like rain? The answer is that they do fall; but, because of air resistance, the rate is so slow that they evaporate long before they reach the ground. A cloud droplet (usually 0.001 inch or less in diameter) falls no more than a hundred feet or so in an hour. Thus all clouds settle slowly toward the earth unless prevented by upward convection. They seldom reach the ground, because the compression and resultant heating is effective in evaporating them as they drop to lower altitudes.

The next question that might well occur to you concerns the formation of raindrops: Why is it that rain falls from some clouds and not from others? This is not so simple, and even the meteorologists are not sure of the answer. In the first place, however, it is known that droplets cannot form by condensation in perfectly clean, pure air. Every fog particle, every cloud droplet, every raindrop must start with a nucleus of foreign material, the temperature of

which is below the dew point. These nuclei are mostly the molecules of certain gaseous impurities such as sulfur dioxide and the oxides of nitrogen; but particles of salt (present in the air only near the ocean), smoke, and dust are sometimes effective.

Often there are plenty of nuclei (hundreds in each cubic centimeter) so that all the moisture can condense in the form of fine cloud droplets. In such instances, according to one theory of rain formation, no rain will fall. The theory then assumes that sometimes after long-continued periods of upward convection, nearly all the available nuclei are used up. In other words, the air is effectively filtered clean by the formation of many droplets lower down. In such cases, the condensation on the few nuclei available must, of necessity, result in the growth of large drops—the fewer the nuclei, the larger the drops. These drops fall as rain, often gathering to themselves additional small droplets as they penetrate the lower portion of the cloud.

To sum up, then, the formation of raindrops large enough to fall at an appreciable rate probably depends on two conditions: *first,* updrafts of warm, moisture-laden air, with the attendant expansion, cooling, and condensation; *second,* filtration of the air by the formation of many small droplets in the lower part of the cloud, leaving, higher up, only a few nuclei on which drops can be built.

It is said that sometimes, in the tropics, rain falls from a clear, cloudless sky. Evidently, such a phenomenon might be possible, provided the air has already been cleansed of nearly all foreign matter by a previous cloud or rain formation. So few nuclei then remain that only large drops can form.

The conditions necessary to produce the frozen forms of precipitation—hail, snow, and sleet—are very similar to the requirements for rain, with the freezing temperatures always required at some stage of the process. Hail is usually formed high up in a thundercloud, where the temperature is below freezing. Large hailstones are grown from small ones by the addition of layer after layer of ice, when the stone is repeatedly thrown upward by violent updrafts into the cold upper region of condensation. Hailstones as large as walnuts and even apples have been reported. Much smaller stones have been known to smash windows and kill livestock in an open field because of the combined velocity of fall and wind velocity.

Snow is formed when the whole upper atmosphere is below the freezing point. There is then no liquid water present—only ice and

vapor. But the vapor can condense directly into snowflakes, just as it condenses into raindrops when the air is warm. Sleet is produced when moist snow or rain falls on a surface cold enough to freeze it. The thick layers of ice over every exposed surface are very beautiful, but the men who have to repair telephone and power lines, and the householder whose shade trees are broken by the weight of ice on their branches, can be pardoned for their lack of appreciation of sleet.

VIII. *What Is the Origin of Storms?*

The great majority of storms may be classed under one of two headings: *cyclonic storms* and *thunderstorms.* In the temperate zones, most of our winter rain and snow is of cyclonic origin, most of our summer rain of thunderstorm origin.

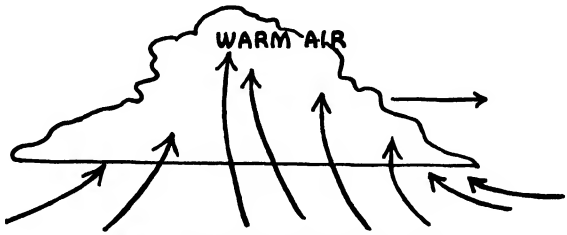
The cyclone we have already discussed in connection with the cause of winds. It consists, as you recall, of a low-pressure central region where warm, humid air is rising, and of a surrounding area where the wind is drawn inward along a spiral path. We might thus expect that the area at or near the center (the place of lowest pressure) would be ideal for the production of rain. This would be true if there were no disturbing factors. For one thing, the cyclone is drifting with the prevailing winds (usually toward the east in the temperate zones). This motion causes distortion. The rising air is located, not at the center, but near the front of the cyclone; and most of the precipitation thus takes place to the east or northeast of the cyclonic center.

But the picture is still oversimplified. The presence of oceans, mountains, or rising plains may so modify conditions that the principal rainfall occurs at quite an unexpected portion of the cyclone. On the Pacific coast, for instance, where the ocean is to the immediate west, the heaviest rain is to the south and west of the cyclonic center.

Thunderstorms, our principal source of rains during the summer, are much more localized than the cyclonic storms, and usually do not last so long. In some regions, thunderstorms occur regularly on every warm summer afternoon. An incipient thunderstorm is characterized by the formation of the towering thunderheads that are so familiar to everyone.

A thundercloud starts with a local rising current of warm, damp air. Once started, it is largely self-generating. When moisture

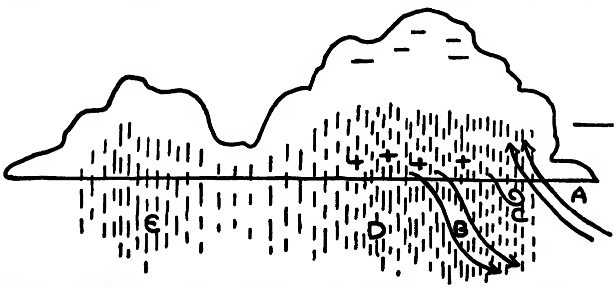
condenses the large quantity of heat liberated serves further to warm the air; the updraft thereupon becomes stronger than it was before;



Development of the thunder cloud.

more moisture condenses; additional heat is liberated; the convection goes on with still greater vigor—and so on, until the whole cumulative process finally comes to a stop high in the cold upper atmosphere. This chimney-like action accounts for the commonly-observed speedy piling-up of the tall thunderheads.

Most rain and snow is electrically charged. But the center of a thundercloud is ideal for the generation of the huge potentials—hundreds of millions of volts—that give rise to the phenomenon of lightning. Large drops of rain, condensed high up in the clouds, are broken to bits as they fall into the turbulent updrafts. As we



A typical thunderstorm. (*A*) Updraft of warm air. (*B*) Downdraft of cold air. (*C*) Roll scud (due to turbulence between ascending and descending columns of air). (*D*) Primary rain. (*E*) Secondary rain.

noted back in Chapter Five, this breaking-up process results in negative electrification of the smaller drops, and positive electrification of the large drops. The positively-charged large drops tend to fall; while the small negative drops are swept upward once more by the convection. Thus, the lower portions of the clouds are often charged positively while the upper portions are negative.

Though the initial convection inside a thundercloud is always upward, conditions are altered once the rain begins to fall. Evaporation of the falling raindrops withdraws heat from the air with the result that a cold downdraft is immediately generated. This accounts for the sudden drop in temperature that commonly accompanies a thunderstorm. The warm, humid air still rises at the upper, advancing front of the cloud. But farther back, a cold draft blows downward, and sweeps across the earth like a wedge being driven under the rising column of warm air. This is the cold wind that we normally experience just before and during the rainfall.

Thus, every thunderstorm accompanied by rain involves two currents of air: a strong updraft of warm air, and a neighboring downdraft of cold air. As you might expect, there is violent turbulence at the boundary between these counter-currents.

IX. *How Is Weather Predicted?*

The term *climate* refers to average conditions of temperature, wind, precipitation, and the like over a period covering several seasons or years. *Weather,* on the other hand, refers to the day-to-day variations in the climate.

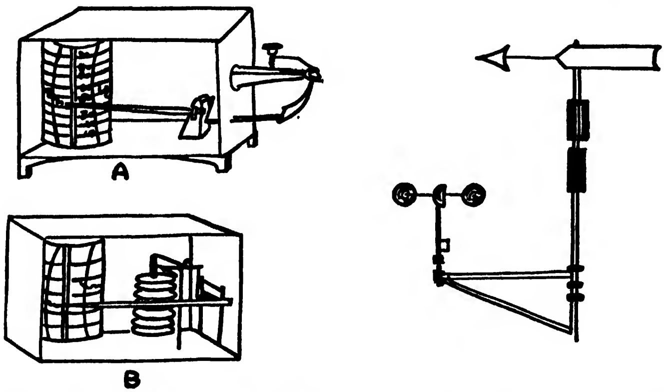
Climate is determined primarily by the quantity of radiation received from the sun: The climate is hot at the equator, because there the earth receives much radiation from the sun; it is cold at the poles because those regions receive little radiation; we have summer when the earth is tilted on its axis so that we receive the full blast of the sun's rays; we have winter when the rays strike the earth's surface more obliquely.

In local areas, however, the climate is greatly influenced by many other factors: prevailing winds (hot or cold; dry or damp), oceans and large lakes (which tend to maintain uniform temperature), ocean currents (warm from the equator, cold from the polar regions), continents, and mountain ranges are a few of the agents that are important in modifying the climate.

In any one locality, the climate changes markedly with the altitude. The temperature of the air normally decreases 1° F. for each 300-foot rise—about 18° F. per mile. This means that the average temperature at the top of a tall mountain must be well below freezing. As you know, many mountains, even those in the equatorial regions, are covered with snow the year around. Also, the daily temperature variations at high altitude are greater than at sea level.

The thin, dry air above a mountain does not form a very efficient protective blanket from the heat of the sun; nor does it prevent rapid radiation and cooling at night. Since water vapor in the air is the chief agent that is effective in trapping radiation, these same extremes between day and night temperatures are often observed in dry desert regions.

Though meteorologists are interested incidentally in climate and its causes, there is a tendency in this day of specialization for the true meteorologist to limit his activities to the prediction of day-to-day changes in the weather. Climate enters into these forecasts only in a general way. From what you have already learned about winds and storms, you should have a pretty good idea of the measurements that must be taken in order to predict the weather. These measure-



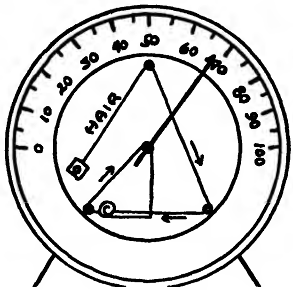
Some meteorological instruments. (*A*) Recording thermometer. (*B*) Recording barometer. (*C*) Anemometer and weather vane to show speed and direction of wind.

ments include records of temperature, pressure, cloud formation, precipitation (kind and amount), humidity, wind direction, and wind velocity.

When a meteorologist has recorded all the necessary data at his own station, he has by no means finished his work. He is not even prepared to make a satisfactory local forecast of the weather. Twice a day, sometimes oftener, the reports from many different stations all over the country, and even from ships at sea, are sent by telegraph and radio to the district forecasting headquarters of the United States Weather Bureau. At these district offices, *weather maps* are prepared, which chart the temperature, the pressure, the precipita-

tion, and the nature of the clouds and winds for the whole United States.

Perhaps the principal feature of a weather map is the series of lines, called *isobars,* joining points of equal pressure. These lines show clearly the position of cyclones and anticyclones, because the isobars form closed circular or oval paths around the center of either a low-pressure or a high-pressure area. The words *low* and *high* are printed on the map at the centers of the cyclones and anticyclones, respectively.



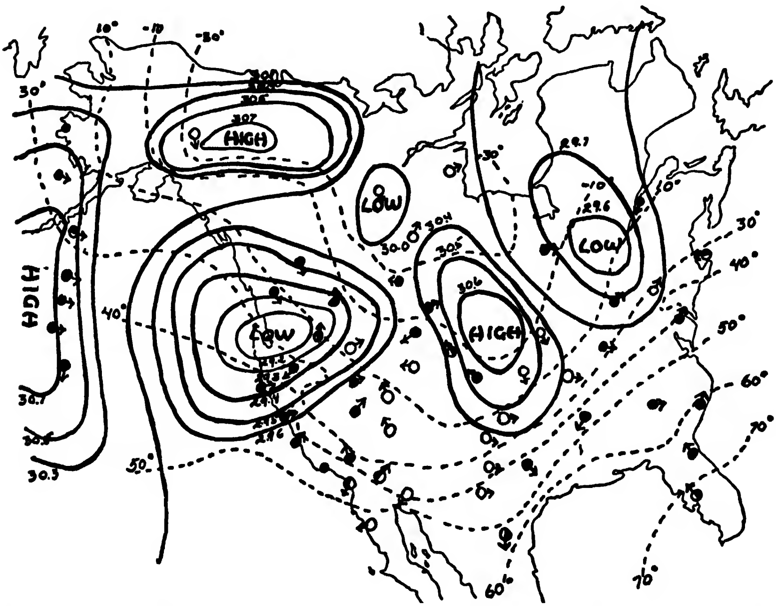
The hair hygrometer measures relative humidity. A human hair attached to a pointer, expands when the air is damp, contracts when it becomes dry.

Other lines, called *isotherms,* are also drawn on the weather map. These join points of equal temperature. The direction and velocity of the wind is indicated by arrows. The areas which are cloudy and in which rain is falling, are shown by shading or by other means.

By studying a weather map, an expert meteorologist can make a reasonably accurate prediction of the weather for one, two, sometimes several days ahead. He knows, for instance, that cyclones normally travel in well-marked storm routes across the country—generally in an easterly direction, at a speed of 20 to 30 miles per hour. He can thus predict, approximately, the time that a storm will arrive at any given point. At any rate, he can do this provided the cyclone does not disintegrate or unexpectedly shift its path before it reaches the point in question. From the other data, he can indicate the expected changes in temperature, and he can forecast in a general way the nature and amount of the precipitation that is likely to accompany the storm.

In the last few years, considerable progress has been made in weather forecasting by the introduction of the *air mass analysis*

method. This involves taking meteorological data, not only at the surface of the earth, but high up in the atmosphere as well. The high-altitude data are obtained either by aeroplanes or by small free balloons. The balloons carry light-weight instruments that send automatic radio reports back to the station at regular intervals. Today at a number of stations in the United States, aeroplane or balloon observations are made daily for the purpose of obtaining these upper-air data.



A typical winter weather map. Full lines are isobars (joining points of equal pressure); dotted lines are isotherms (joining points of equal temperature); arrows (located at the position of every reporting ship or station) indicate direction toward which wind is blowing. Cloudiness is shown by blackening of the tails of the arrows. On actual weather maps, rain, fog, snow, and wind velocities are indicated by various devices.

It has long been known that conditions of temperature, humidity, and pressure at high altitudes are often quite different from what one would expect on the basis of surface observations. Furthermore, it is only reasonable to suppose that the state of affairs in the upper atmosphere is of primary importance in determining the weather down below. Such is the case.

It is found that cyclones and anticyclones are not in themselves primarily responsible for the weather. Rather it is the interaction between moving masses of warm and cold air. Many cyclonic storms are generated in the region where warm humid masses of air from the tropics collide with cold masses bearing down from the north pole. The "front" or boundary between the two masses is seldom vertical; it goes up obliquely, with the cold mass forming a wedge under the warm upper air. This wedge may extend for hundreds of miles. As a result, the presence of the all-important warm mass, hovering high overhead, would be totally unexpected from observations taken at the surface of the earth.

Weather maps that are essentially three-dimensional are now being prepared. These maps show, not only the surface conditions, but also the location of the boundaries between the warm and the cold air masses. In some localities, as on the Pacific Coast and on the Great Plains, the air mass analysis method has proved phenomenally successful in predicting weather conditions for some days ahead. These forecasts have been extremely valuable to the commercial airlines. They have also saved much time and money for the motion picture companies in planning "shooting schedules" on outdoor sets.

In the eastern part of the United States, air mass analysis has proved helpful; but it is by no means a panacea for the troubles that beset the weather man. This region of the country, especially along the North Atlantic seaboard, is very often a meeting point for the frigid polar air masses and the warm tropical masses. Consequently, the atmosphere is in an unstable state, and local storms may appear or disappear within a few hours.

When forecasts go wrong, everyone blames the poor weather man. But it is not his fault; he is doing the best that anyone knows how. The vagaries and uncertainties of the atmospheric behavior are responsible. But as the air mass analysis method comes into wider use in the future, we may expect further improvement—even, perhaps, accurate predictions for weeks ahead.

It is too early yet to guess what improved methods of weather forecasting will appear as a result of the work of meteorologists in the last war. The technique of air mass analysis had its beginning during the first world war, when the Scandinavian countries were cut off from their usual sources of weather information throughout the world, and therefore had to turn to a more intensive study of the

atmosphere over their own terrain. It may be that some equally important innovation is in store for us within the next few years. Meanwhile, we shall have to endure a little uncertainty about whether to take the umbrella along when we leave home in the morning.

CHAPTER ELEVEN

WAVES, SOUND, AND MUSIC

I. *What Is a Wave?*

Earlier in this book, particularly in connection with light, we talked frequently about waves and wave motion. Waves are very common. Probably you see water waves every day of your life (at least small ones in the sink or basin); you make use of light waves in order to see the water waves; you hear sounds by means of air waves. And yet, despite the fact that wave motion is everywhere, can you explain just what happens inside a wave?

When you stop to think about it, waves are peculiar. You see a wave skimming along the surface of the ocean—but what travels with the wave? The water certainly does not. A stick floating on the surface is displaced as the wave front moves past; but afterwards (except in the case of a breaking wave), the stick returns to its original position. We recognize that waves carry energy. No one who has ever seen the ocean dashing against a sea wall during a storm could doubt that. But how is this energy transmitted, if the water itself does not travel with the wave?

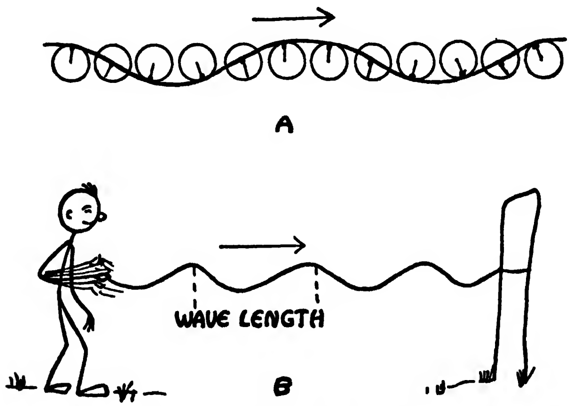
As is often the case in nature, the commonest things are the most complicated. This is true of water waves. Inside a water wave, the water particles move in circular or elliptical paths. Eventually, after the motion passes on to the neighboring mass of water, the particles return to rest at the place where they started. But it is difficult to understand how this works.

We can see better what happens in a wave traveling down a stretched rope or wire. Suppose that you fasten one end of a rope to a post, and, holding on to the free end of the rope, jerk your hand up and down. A wave starts down the rope from your hand to the post. At a point where the wave is passing at any instant, the rope moves up and down vertically, while the wave itself moves horizontally.

If, instead of giving a single jerk, you move your hand rhythmically up and down while you hold on the end of the rope, a series of waves will be generated—one complete wave for each up-and-

down motion of your hand. In a train of waves of this kind, the particles of the rope move up and down with simple periodic motion; that is, they oscillate like a clock pendulum, or like a bob vibrating on a spring. Energy is thus transmitted down the rope by means of an oscillatory motion of the rope sections.

Although water waves, waves in a string, light waves, and sound waves differ from one another in detail, they are all alike in certain respects: they serve to transmit energy through a medium by means of vibrations of the particles, without permanently altering or dis-



(*A*) Water waves: the particles move in circles. (*B*) Waves in a stretched string.

placing the medium as a whole. Any disturbance that fulfills these conditions may be called a wave.

As you know already, the number of complete vibrations per second is called the *frequency*. You recall, too, that the distance between successive crests (or between successive valleys) in a wave is called the *wave length*. Hence, the frequency is also equal to the number of complete waves (crests or valleys) passing a given point each second.

There is always a simple relationship between the velocity of the waves V, the frequency F, and the wave length L:

$$V = F \times L$$

This is an important equation, and it holds for any kind of wave motion. We shall make use of it later for both sound waves and radio waves.

II. *What Are Sound Waves?*

During the Middle Ages, philosophers spent many long hours discussing the following question: If a tree crashes to the ground far out in the forest where there is no one to hear it, does it make any sound? Even today this same question is revived from time to time, and some people still cannot agree on the answer.

If you are puzzled by the question, it behooves you to do first what the philosophers of the Middle Ages should have set out to do before they wasted their time in fruitless debate: you should decide what you mean by the term *sound*.

Earlier, we said that sound is a wave motion in the air. This is a physicist's concept. If you accept this viewpoint, the answer to the tree question is obvious: The waves *are* generated, and hence there is a sound whether anyone is present to hear it or not.

On the other hand, the psychologists and physiologists might not agree with this definition. They might say, justifiably enough, that sound is not a wave motion but a sensation—it is something that our ears telegraph to the brain, something that we hear. Obviously, with this definition of sound, the tree question would have quite a different answer: There is no sound unless someone hears it.

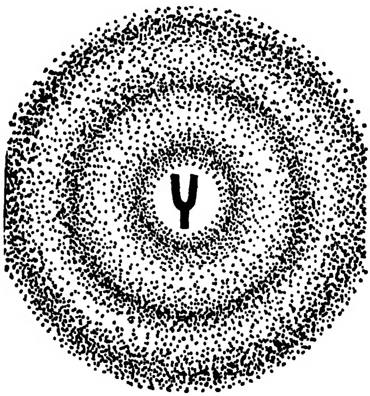
So the question of the falling tree may be answered correctly either "Yes" or "No," depending on whether you define sound as a wave motion, or as a sensation produced by the wave motion. Since this is a book about physical things, let us, for the sake of convenience, retain our physical definition; namely, that sound is a wave motion.

Usually, sound is transmitted to our ears through the air. It may, however, be transmitted through any elastic medium, such as water, steel, rock, or wood. You know, for instance, that you can hear a noise in the next room, even though the doors are tightly shut. Perhaps you have listened at one end of an iron pipe or rail when someone was hammering at the other end. The sound was transmitted through the iron clearly and with little loss of intensity. But, unlike light, sound cannot be transmitted through empty space. This may be proved readily enough by suspending an electric bell or other sound-maker inside a closed vessel which can be evacuated. As the air is pumped out, the sound of the ringing bell fades away to nothingness.

Sound waves in water have important military uses. The vibrating hull and churning propeller of a ship or a submarine send

out into the water a train of sound waves which can be detected several miles away. With experience, the sound observer in a submerged submarine can get a very helpful idea of what the surface craft in his neighborhood are doing. In one method of locating submarines, a pulse of high-frequency sound is sent out into the water in a sort of beam, and the observer "listens" (usually with complicated electrical devices) for the echoes.

That sound is actually a wave motion, is suggested perhaps from the fact that it is generated by vibrating objects—tuning forks, piano strings, reeds, and the like. But, like light, sound travels in



Sound waves emitted by a tuning fork: showing the regions of compression and rarefaction in the air.

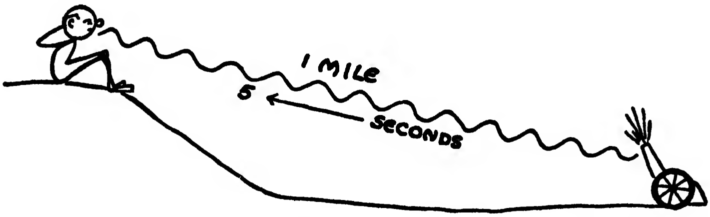
three dimensions—it does not merely spread along a two-dimensional surface like water waves, or along a single dimension like the waves in a string. The crests of the sound waves are spheres of compression in the air; the valleys are spheres of expansion. The air molecules vibrate back and forth with simple periodic motion, not at right angles, but in the same direction as the wave itself is traveling. For this reason, sound waves are called *longitudinal*, or *compressional* waves. The wave length is the distance between successive crests of compression, or between successive valleys of expansion.

The velocity with which sound waves travel can be measured readily. There are precise laboratory methods; but you yourself could measure the velocity of sound in a somewhat crude fashion as follows: Have a friend stand a measured distance (say, a mile) away, and let him fire a gun into the air. The time between the

flash or puff of smoke (remember that the light reaches you almost instantaneously since it travels 186,000 miles per second) and the arrival of the report of the shot will give you the velocity of sound:

$$Velocity = \frac{Distance}{Time}$$

If you measured the time very accurately with a stop watch, you would find that it took nearly 4.7 seconds for the sound to reach you from a distance of a mile (at a temperature of 20° C.). In other words, the velocity of sound is 5280/4.7, or 1130 feet per second—770 miles per hour.



The velocity of sound in air. The report of the gun reaches the observer one mile away about 5 seconds after he sees the flash.

Sometimes it is interesting to perform this same experiment in reverse; that is, to determine the distance to a source of sound by timing the arrival of the sound. Suppose, for instance, that you wish to find out how far away a flash of lightning is. You need only measure the time between the flash and the first peal of thunder. The distance in feet will be given by:

$$Distance \text{ (feet)} = 1130 \times Time \text{ (seconds)}$$

Or, for most practical purposes, it will be close enough to assume 5 seconds for each mile.

Note that you should time the arrival of the *first* peal of thunder. This will give you the distance to the closest part of the lightning flash. Thunder rolls and rumbles for a considerable time, for several reasons. A large majority of the strokes are multiple, many sparks occurring down the same path (as many as 40 have been observed) in succession within a second or two. However, most rumbling you hear is the echo of the strokes repeated from clouds and mountains, chiefly clouds.

Echoes, as you doubtless know, are simply reflected sound waves. As in the case of light, at least partial reflection occurs whenever

the waves encounter a medium different from air—for instance, a cliff, a forest, even a cloud, where there are large temperature and density changes.

The velocity of sound is independent of the air pressure; that is, it is independent of the barometer reading. It does, however, vary with the temperature; the higher the temperature, the greater the velocity. For every degree centigrade rise in temperature, the velocity of sound in air increases approximately 2 feet per second. As we shall see later, this causes pipe organs and other wind instruments to be out of tune when the temperature rises or falls an appreciable amount.

III. *Why Do Sounds Differ from One Another?*

There is a vast difference between the boom of a cannon and the musical note that comes out of an organ pipe; yet both sounds originate as air vibrations in hollow tubes. The clatter of empty tin cans is hardly to be compared with the pleasing notes of the chimes; yet both sounds are produced by blows on hollow metal vessels. A child, pounding on a stick of wood with a hammer, makes only a noise; yet a xylophone player, pounding on slabs of wood with a mallet, is able to produce sweet music.

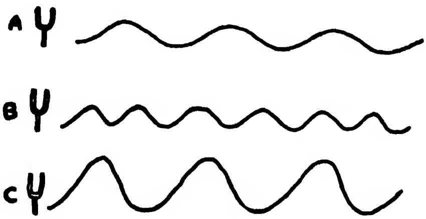
What is the difference between those raucous sounds that we call noise, and the more melodious tones that we recognize as musical notes? Simply this: a noise is a train of sound waves that is of such short duration, or is so irregular in intensity and frequency, that the ear can make no sense out of it. A musical note, on the other hand, is a wave train of long duration and of fairly uniform frequency and intensity. Thus, there is no hard and fast rule distinguishing music from noise. The difference is one of degree. Moreover, it is largely a matter of training. Some combinations of tones are pleasing to one person but not to another. Much of Wagner's music, for instance, is scarcely more than a jumble of noises to the untrained ear; but a musician may consider the same music to be the greatest in the world. Certainly, to our civilized ears, the beating of tom-toms and the chanting of the native tribes in Africa is not melodious; yet it is music to the Africans.

Let us agree, however, that from a physical viewpoint, a ***pure musical note*** is a true simple periodic motion—a uniform vibration with constant intensity. Such a tone is emitted by a tuning fork, for instance. But, as a musical instrument, a tuning fork would

be pretty dull and uninteresting. Its tone is too pure. Real musical instruments emit more complex tones—combinations of several simple periodic vibrations.

When you hear a musical note, you classify it in your mind according to three characteristics: *pitch, quality* (or *timbre*), and *loudness.* We wish to see now how these differences sensed by your ear depend on the physical nature of the vibration.

The *pitch* of a tone depends chiefly on the frequency of vibration: the higher the frequency, the higher the pitch sensed by the ear. Thus, a low-pitched fog horn may have a frequency of 100 vibrations per second; a high-pitched whistle or siren, a frequency of several thousand vibrations per second. On the *scientific musical scale,* the note middle *C* has a frequency of 256 vibrations per second; the note *c*, one octave above middle *C*, has just twice the frequency of middle *C*, or 512 vibrations per second. Though the pitch seems



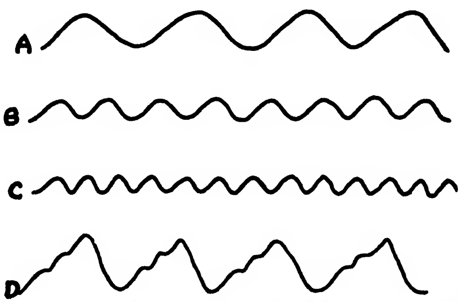
(*A*) Graphical representation of the sound waves in a pure musical note. (*B*) A note of higher frequency (higher pitch). (*C*) A louder note.

to our ears to depend principally on frequency, it also varies somewhat with loudness. Thus, middle *C*, played very loudly, will seem flat (lower pitched) compared with the same note played softly. This slight decrease of pitch as the loudness increases is observed with all low-frequency notes up to about 1,000 vibrations per second. On the other hand, a very high frequency (several thousand vibrations per second) seems to increase in pitch as its loudness is increased.

Even to the untrained ear, the same note sounds entirely different when played on a pipe organ and when played on a piano. Trained musicians can pick out and identify practically every instrument in a large orchestra—even when all the instruments are being played at the same time. This is possible because each instrument has a *quality* all its own. The instruments may all be playing the same

note—that is, the same fundamental frequency—yet they sound quite different from one another.

Physically, the quality of a tone is determined by the number and the intensity of the different pure tones that are present. When you play middle C on an instrument, not only the fundamental note of frequency 256 is emitted: so are *overtones,* or *harmonics,* of frequencies 2×256, 3×256, 4×256, etc. In some instruments, the overtones are relatively strong; in others the overtones are weak; in still others certain overtones are missing completely.



The fundamental note *A* of frequency *f* combines with the overtones *B* and *C* of frequencies *2f* and *3f* to give the complex wave *D.*

Loudness, the third characteristic of sound, depends principally on the amplitude of the vibration; or, if you prefer, on the rate at which sound energy is received by the ear. But the sensation of loudness depends also to some extent on pitch and quality. For example, at low intensity, high C sounds louder than middle C when the energies are equal. Even at any one frequency, however, the sensation of loudness is by no means proportional to the power (the rate of flow of sound energy), or the intensity of the sound. In fact, a ten-fold increase in power normally does no more than double the sensation of loudness in the ear.

This peculiar response—actually, lack of sensitivity—exhibited by the ear to changes in sound intensity is very important. It enables us to hear extremely faint sounds which supply power to the ear at the rate of only 10^{-16} (0.0000000000000001) watt per square centimeter—an inconceivably small amount of power. But at the same time, the power may be increased a trillion-fold to 10^{-4} (0.0001) watt before the sound is loud enough to be painful to the ear. Power of 10^{-16} watt per square centimeter corresponds to the

faintest audible whisper; 10^{-4} watt per square centimeter to the din in a boiler factory.

Nowadays, one frequently sees the *loudness level* of sound expressed in a unit called the *decibel.* The decibel is one-tenth of a *bel,* a unit named in honor of Alexander Graham Bell (1847–1922), the inventor of the telephone. The definition of the decibel is rather technical; but the unit is coming into such common use that it may be worthwhile to explain its significance. Each time the power received by the ear is *multiplied* by 10, 10 decibels (one bel) are *added* to the loudness scale. This means that the power scale increases very much faster than the corresponding decibel scale. The threshold of

	LOUDNESS LEVEL D.B.	POWER WATTS/SQ C.M.
PAINFUL SOUND	120	10^{-4}
AIRPLANE MOTOR CLOSE BY	100	10^{-6}
NOISY STREET	80	10^{-8}
CONVERSATION	60	10^{-10}
QUIET AUTOMOBILE	40	10^{-12}
WHISPER	20	10^{-14}
THRESHOLD OF HEARING	0	10^{-16}

The loudness level in decibels of some common sounds. For comparison, the power in watts per square centimeter is also shown.

audibility, 10^{-16} watt per square centimeter, is often taken as zero decibels. Ten times as much power, 10^{-15} watt, is equivalent to 10 decibels; ten times as much power again, 10^{-14} watt, is equivalent to 20 decibels; and so on, up to the point where the sound becomes painful to the ear at 10^{-4} watt per square centimeter—where the decibel scale reads 120. Thus, while the power is being multiplied by a trillion (10^{12}) the decibel scale increases from 0 to 120. If you are mathematically inclined you will realize that the loudness in decibels is proportional to the *logarithm* of the power (or intensity).

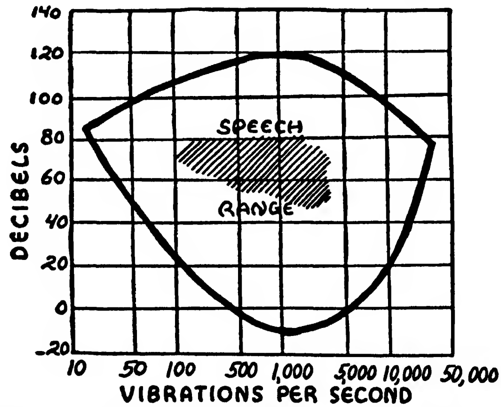
If this discussion of power and decibels does not make much sense to you, simply remember that the decibel is essentially a unit of loudness: the more decibels, the louder the sound. Zero decibels is the

point where sound just becomes audible; an ordinary whisper is about 20 decibels; average conversation runs 60 to 70 decibels; a pneumatic drill close by makes a noise at the level of about 100 decibels; a din becomes painful to the ear at 120 to 130 decibels. Incidentally, a change in loudness of one decibel is about the least variation that can be detected by the ear.

IV. *How Does the Ear Detect Sound?*

Now that we know something about *what* we hear, the next question is: *How* do we hear? In other words, how does the ear function?

The ear is indeed a remarkable mechanism; and it is so complicated that its operation is none too fully understood. Certainly it is



Limits of audibility for the average ear (area enclosed in heavy lines), showing how the sensitivity of the ear decreases at low and at high frequencies.

extremely sensitive. At the threshold of audibility, the power requirement (10^{-16} watt per square centimeter) is inconceivably tiny. If all the people in the United States—130,000,000 of them—were listening simultaneously to a whisper (20 decibels), the power received by all of their eardrums together would total only a few millionths of a watt—far less than the flying power generated by a single mosquito.

The ear is remarkable, too, for its ability to distinguish between various pitches and qualities of sounds. In the range of frequencies where the ear is most sensitive (500 to 4,000 vibrations per second), changes in pitch of 0.3 per cent can be detected. Thus, if a singer

trying to reach the octave above middle *C* (512 vibrations per second), is off key by only 1.5 vibrations per second, the fault can be detected.

The normal ear can respond to frequencies ranging from 20 to 20,000 vibrations per second.* In this range it is estimated that the ear can distinguish more than half a million separate pure tones; that is, 500,000 differences in frequency, loudness, or both.

The versatility of the ear becomes all the more wonderful when you remember that many different qualities of sound can be distinguished, even though the many sources (as, for example, the instruments in an orchestra) are all emitting the same fundamental frequency at the same time.

Then, too, we are able to tell approximately the direction from which sound comes. This is possible chiefly because we have two ears instead of one. The sound arrives a split second later at one ear than at the other, and the brain by experience interprets this phase difference in terms of direction.

Besides detecting sound, a portion of the ear has another entirely different function: The semicircular canals enable us to maintain our equilibrium.

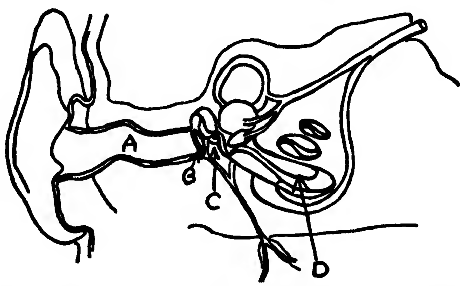
The mechanism by which the ear accomplishes all these tasks is very complicated, and is to a great extent still a matter of speculation. It is easy enough to dissect the ear and see what is in it; but it is another matter to find out what makes it work. The methods by which the physical response to sound is telegraphed to the brain along the auditory nerves, and the interpretation placed on these signals by the brain itself, are subjects far too complicated for us to discuss here.

The ear is divided into three parts: the *outer ear*, the *middle ear*, and the *inner ear*. The outer ear consists of a canal closed at the inner end by a membrane, the *eardrum*. The middle ear contains a system of three bone levers, known as the *hammer*, the *anvil*, and the

* The range varies somewhat from ear to ear, and becomes considerably shorter for low-intensity sounds. Above the audible range, air vibrations similar to sound are called *supersonic* vibrations. These may be generated and detected by electrical devices, and are useful for several purposes—especially in depth sounding at sea. The time for the waves to travel from the generator to the bottom of the ocean and back again is a measure of the depth. Supersonic vibrations apparently can be heard by some animals—notably bats. It is believed that bats are guided during flight, not by sight, but by supersonic "sounds" emitted by themselves and reflected back to their ears from various surfaces and obstacles.

stirrup. These bones serve to transmit the sound vibrations from the eardrum to the membrane-window covering the inner ear. The principal feature of the inner ear is the *cochlea,* a peculiar spiral bony enclosure that looks much like a snail shell. Contained in the cochlea is the vital organ of hearing, the *basilar membrane,* which is about 0.01 inch wide, and when uncoiled, is scarcely more than an inch in length.

Surrounding the basilar membrane is a liquid. The sound vibra-



Structure of the ear. (*A*) Outer ear. (*B*) Eardrum. (*C*) Middle ear containing the hammer, anvil, and stirrup. (*D*) The inner ear containing the cochlea and basilar membrane.

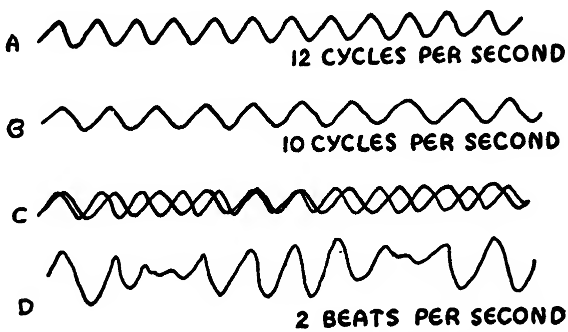
tions are transmitted to this liquid, and then, apparently, through the liquid a certain distance depending on the frequency. Lower frequencies are transmitted to the farther end of the basilar membrane; higher frequencies are able to penetrate only a short distance through the liquid. Along the basilar membrane are located the auditory nerve endings. When a particular portion of the basilar membrane is stimulated by the sound vibrations, the brain records the disturbance as a certain pitch. More vigorous oscillation is interpreted as a louder sound.

V. *What Is a Musical Scale?*

If combinations of two or more frequencies are sounded simultaneously, the ear may interpret the result in a number of different ways, depending on the particular tones that are present. We have already noted how the presence or absence of overtones (frequencies 2, 3, 4, etc., times the fundamental) can affect the quality. Shortly, we shall investigate some of the other combinations that are especially pleasing to the ear, and are therefore utilized in musical compositions.

For the moment, however, let us see what happens when two notes of very nearly the same frequency are sounded together. Suppose, for example, that we have two similar piano strings, one making 440 vibrations per second (note *A*) and the other slightly out of tune, making 442 v.p.s. When these two strings are set into vibration simultaneously, we hear a rather peculiar effect: The note *A* is recognizable, but the intensity of the sound waxes and wanes—two maxima and two minima occurring each second. These variations in loudness are known as *beats*. The number of beats per second always equals the difference between the two nearly-equal frequencies that are sounded simultaneously.

Beats are caused by interference of the wave trains coming from the two sources of sound: 442 complete waves are emitted from one



The formation of beats by interference between two waves (*A*) and (*B*) of frequency 12 and 10 vibrations per second, respectively. (*C*) shows the two waves superimposed. (*D*) shows the resultant wave, waxing and waning twice each second.

source each second; 440 from the other source. As these two wave trains race past the ear, the disturbances in the air will be in phase, and will add up to a maximum intensity, twice each second. But also, twice each second, the waves will be out of phase (that is, crest will meet valley) and the two disturbances will just cancel each other. This destructive interference results in zero intensity; hence, the "throbbing" or waxing and waning of the sound.

When the difference between the two frequencies becomes greater than 15 or 20 v.p.s., distinct beats are no longer heard. Instead, along with the two original notes, a new note is present, equal to the difference between the two frequencies. In general, the result

is an unpleasant roughness, known as *dissonance*—a sort of noise rather than a musical note.

If, however, the difference in frequencies is still further increased, a harmonious combination, known as *consonance*, is eventually attained. The ratio of the frequencies of two consonant notes is called a *musical interval.* Such combinations are of frequent occurrence in musical compositions.

The best possible consonance is obtained when the two notes are in perfect unison; that is, the frequencies are exactly equal. The next most consonant musical interval is the octave, where the frequencies are in the ratio 2: 1. In fact, any interval where the ratio of the frequencies can be expressed in terms of small, whole numbers is considered to be consonant.

The musical names of some of the commonest intervals, together with their frequency ratios, are as follows:

Interval	*Frequency Ratio*
Unison	1: 1
Octave	2: 1
Fifth	3: 2
Fourth	4: 3
Major third	5: 4
Minor third	6: 5
Major sixth	5: 3
Minor sixth	8: 5

The names of the intervals are derived from the relative positions of the two notes on the musical scale. Thus, the *octave* is the combination of the first and *eighth* notes on the scale, the *fifth,* the first and *fifth* notes.

Such intervals as 7: 6, 8: 7, 16: 15, and 25: 24 are sometimes used, but may be unpleasant to the ear unless carefully handled. So-called modern music is especially bold in the use of combinations of notes that were considered dissonant by the writers of classical music.

Musical scales are based not so much on musical intervals (combinations of two notes) as on *triads* (combinations of three notes). It is found, for instance, that the frequency combination 4: 5: 6 is especially pleasing to the ear. The *major diatonic scale* is so constituted that a number of these major triads are available.

There are seven notes in any one octave of the major scale. Be-

ginning with the note middle *C*, the frequencies in vibrations per second,* the intervals, and the triads are as follows:

Name	*Do*	*Re*	*Mi*	*Fa*	*Sol*	*La*	*Ti*	*Do'*	*Re'*
Note	*C*	*D*	*E*	*F*	*G*	*A*	*B*	*c*	*d*
Frequency* (v.p.s.)	264	297	330	352	396	440	495	528	594
Interval between each note and C	1:1	9:8	5:4	4:3	3:2	5:3	15:8	2:1	
Interval between adjacent notes		9:8	10:9	16:15	9:8	10:9	9:8	16:15	9:8
	4		5		6				
Major triads					4		5		6
				4		5		6	

The frequency ratios or intervals are the same in all octaves; but the frequencies themselves are multiplied by two in each succeeding higher octave.

You will notice that there are three different intervals between adjacent notes: *a major tone*, 9: 8, *a minor tone*, 10: 9, and a *half tone*, 16: 15.

Besides the major triad with ratio 4: 5: 6, it is found that another triad of notes in the ratio 10: 12: 15 is a pleasing combination of frequencies. The *minor diatonic scale* is built up on this triad. In order to provide the necessary frequencies for the minor triads, five more notes are added to each octave of the major scale. These are the *sharps* and *flats*, or the black keys on the piano. They are inserted between the pairs of major scale notes that are separated by whole tones; that is, between *C* and *D*, *D* and *E*, *F* and *G*, *G* and *A*, *A* and *B*. Thus there are altogether twelve notes (7 majors and 5 minors) in each octave, with a half tone interval between each pair of notes.

With only twelve diatonic notes for each octave, it would be impossible to play a musical composition in any key but the key of *C*. A violinist can obtain any pitch by depressing the strings at the correct points. But an instrument of fixed frequencies like the piano is not so flexible. If a piano were tuned to the diatonic scale, many of the intervals needed to make up the major and minor triads would

* The frequencies given in the table are based on the *philharmonic* pitch, with the note *A* set at 440 vibrations per second. This is the present-day standard for piano and orchestral instruments. On this scale, middle *C* has a frequency of 264 instead of the 256 v.p.s. of the scientific scale. Sometimes, instruments are tuned to an *A* of 435 v.p.s.; and some years ago, the so-called *concert pitch*, with an *A* of 450 v.p.s. was popular, but has now been largely abandoned (except by British army bands) as undesirably high.

be missing, unless the basic note were always taken as *C*. In fact, to play music in all twelve keys would require some 70 notes in every octave. A piano keyboard with the present number of keys multiplied by 5 or 6 would be cumbersome, to say the least.

In order to obviate the necessity for multiplication of notes, and yet enable the performer to play music in any desired key, a compromise scale is adopted. This is known as the *tempered scale,* and the intervals between each of the twelve successive notes of an octave are equal. The necessary half tone interval is the twelfth root of 2, or about 1.06. That is, the frequency of each succeeding higher note is 1.06 times the frequency of the neighboring lower note. Thus, if the frequency of *A* is taken as 440, *A*♯ (or *B*♭) is 1.06×440; *c* is $(1.06)^2 \times 440$; *c*♯ (or *d*♭) is $(1.06)^3 \times 440$; and so on up to *a* (an octave above middle *A*) which has a frequency of $(1.06)^{12} \times 440$, or 2×440.

Some of the notes on the piano are nearly one per cent (several vibrations per second) different from the strictly correct diatonic scale. This is enough to cause noticeable discord to the trained ear. For this reason, some singers and violinists who pride themselves on their true pitch do not like piano accompaniment. Nevertheless, the simplicity of the tempered scale justifies its use on fixed-keyboard instruments—and most of us are never aware of the slight discord anyway.

VI. *How Do Stringed Instruments Produce Music?*

It is evident that stringed instruments produce musical notes as a result of the vibration of the strings. And the pitch of the note is determined by the frequency of the vibration. But what is it that determines the frequency of vibration of any given string? And how can a single string emit simultaneously a fundamental note plus several overtones?

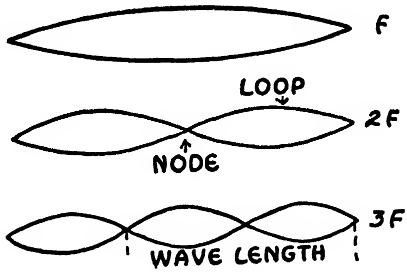
The answer to the first question is summed up in the Law of Vibrating Strings, which may be stated as follows: *The fundamental pitch of a vibrating string varies inversely as the length of the string, directly as the square root of the tension, and inversely as the square root of the mass per unit length.*

If you have ever looked inside a piano, you know that the low notes are emitted by the long, heavy wires; while the high notes come from the short, fine wires. In order to keep the heavy strings flexible and still provide enough weight to attain the desired low fre-

quency, some of the strings are weighted by wrapping extra wire over the main wire.

A violin has only four strings (*G*, *D*, *A*, and *e*, with a musical interval of 3 : 2 between each pair), and these vibrate with comparatively low frequencies. But higher frequencies are attained readily by depressing the strings at various points with the fingers. In accordance with the Law of Vibrating Strings, the shorter the string the higher the pitch. Stringed instruments are tuned by changing the tension: the greater the tension, the higher the pitch.

The pitch is determined by the fundamental frequency of the vibrating string. But the quality, as we have seen, depends on the overtones of higher frequency that are sounded simultaneously. When it is emitting its fundamental note, the string vibrates as a whole, with *nodes* (points where the string remains stationary)



Three modes of vibration of a string: the fundamental frequency f, the first overtone of frequency $2f$, and the second overtone of frequency $3f$.

located at each end, and with a single *loop* (region of maximum vibration) at the center. The first overtone, of twice the fundamental frequency is sounded when the string vibrates in two sections; that is, when there are two loops with a node at the center. For the second overtone, the string vibrates in three sections. For higher overtones, additional *modes of vibration* are present.* The resultant motion of the string is very complex when the fundamental and several overtones are sounding all at the same time.

The lower notes on the piano contain as many as forty overtones. The higher notes have fewer overtones. There has been much con-

* A more complete explanation of the various modes of vibration involves the concept of waves traveling back and forth down the stretched string, with reflection of the waves from the end-supports. Interference between waves going in opposite directions causes *standing waves*, with stationary nodes and loops. The length of a wave in the string is twice the distance between successive nodes.

troversy over the question, whether the "touch" of a piano player can affect the quality of a note—one can find more opinions than experiments, on either side of the question. The mechanism of the piano certainly limits rather severely the way the notes can be struck. The performer can readily vary the loudness and the timing of his successive notes. The relative intensities of the various overtones, however, are, at the most, only slightly under his control.

With the violin and other bowed instruments, the situation is different. Not only can an expert performer vary the loudness and timing, but he can control also the quality by the manner in which he bows the string. The characteristic quality of the violin is due principally to the prominence of the second, third, and fourth overtones; but the relative intensity of the various overtones determines whether the violin sounds melodious or squeaky.

One other important feature of stringed instruments should be mentioned: the sounding board. As the strings vibrate, they transmit some of their motion (through the end supports—not through the air) to the thin sheets of wood back of them. When properly designed, the wooden board oscillates with the same frequency as the string, and radiates the sound energy very effectively because of the great area of contact with the air. As you can verify by listening closely to a piano, most of the sound comes from the soundboard rather than from the strings themselves. Similarly, when you pluck the tines of an ordinary dinner fork, holding the handle in your hand, you can hear the vibrations only faintly. But if you hold the handle against the wooden dining room table after plucking the tines, the sound is much louder.

For a good tone quality, the soundboard in an instrument must respond evenly to all frequencies. This means that the natural vibration frequency of the board must be well below the frequencies of the strings. Otherwise, the board will resonate in unison with certain notes, and unpleasant loudness—even rattling and "screeching"—will result.

VII. *How Do Wind Instruments Produce Music?*

Wind instruments, like stringed instruments, rely on vibrations for the production of music. In the wind instruments, air columns instead of strings are set into vibration.

Let us begin by discussing organ pipes, since they are the simplest of wind instruments. But, first, let me point out a fact that you

probably know already: the pretty gilt pipes that you see on the outside of an organ loft are nearly all only decoration. Most of the pipes that actually produce the music are quite different in appearance and are hidden from view. Some organ pipes are made of metal, but the majority are constructed of wood and are square in shape.

When air is blown across the specially constructed opening, or lip, of an organ pipe, the air column in the pipe is set into vibration. The wave length, and hence the frequency, is determined by the length of the pipe.

The quality (presence or absence of overtones) of an organ pipe depends on the shape of the pipe, on the intensity of blowing, and on whether the pipe is open or closed at the upper end. In general, a long narrow pipe emits principally its fundamental note; while a pipe with large diameter relative to the length is strong on the higher overtones. The harder the pipe is blown, the more are the overtones brought out. Because of the wide variations in tone quality attainable, many a musician considers the pipe organ to be the greatest of all instruments.

Let us now investigate in detail the notes emitted by a pipe that is closed at one end. At the closed end the air cannot vibrate appreciably; hence there must be a node at that point. The other end is open; hence the vibration is a maximum, and this end is at the center of a loop. Now, the distance from a node to the center of an adjacent loop is just one-quarter of a wave length. Therefore, *when a closed pipe is sounding its fundamental, the wave length of the emitted note is four times the length of the pipe.*

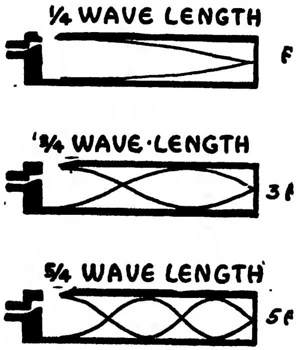
The frequency of the emitted note is given by the formula, $F = V/L$, where V is the velocity of sound (1130 feet per second at 20° C.), and L is the wave length in feet.

For example, a closed pipe one foot long would have a fundamental of wave length 4 feet. The frequency would be 1130/4, or about 283 vibrations per second (nearly C♯). A shorter pipe would be higher pitched, a longer pipe lower pitched.

Since the velocity of sound in air increases with increasing temperature, the frequency emitted by an organ pipe changes correspondingly. In other words, on a hot day the organ is higher pitched than on a cold day. This variation may amount to several per cent.

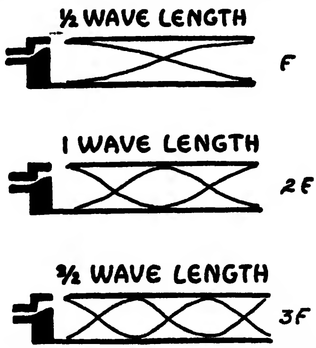
Besides its fundamental note, a closed pipe can emit overtones of frequency 3, 5, 7, etc., times the fundamental frequency. The

requirement of a node at the closed end and a loop at the open end precludes the formation of the even harmonics. That is, the overtones of frequency equal to 2, 4, 6, etc., times the fundamental frequency are missing in a closed pipe.



Diagrams of the vibrations in a *closed* organ pipe sounding (1) its fundamental note of frequency f, (2) its first overtone of frequency $3f$, (3) its second overtone of frequency $5f$.

In practice, most organ pipes are not closed at the top but are left open at both ends. This means that there is a loop at each end, with a node at the center of the pipe. The distance between the centers of adjacent loops is always one-half wave length. Therefore, *the length of an open pipe is one-half the wave length of its funda-*



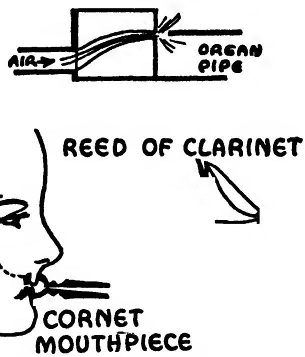
An *open* organ pipe sounding its fundamental f, and its first two overtones of frequency $2f$ and $3f$.

mental note. Open pipes are thus twice as long as closed pipes of the same pitch. To sound middle C (256 v.p.s.) an open pipe must be about $2\frac{1}{4}$ feet in length, compared to $1\frac{1}{8}$ feet for a closed pipe.

By contrast with the closed pipe, the open pipe can sound overtones having any multiple of the fundamental frequency. The quality of the music from an open pipe is thus quite different from the quality of a closed pipe.

Perhaps this discussion of organ pipes seems to you none too simple. But other wind instruments are even more complicated. Of course, we still have to deal with vibrating air columns. And, in general, the length of the column still determines the fundamental frequency. Thus, in the flute and clarinet, the effective length of the air column, and hence the pitch, is altered by opening or closing holes in the tube.

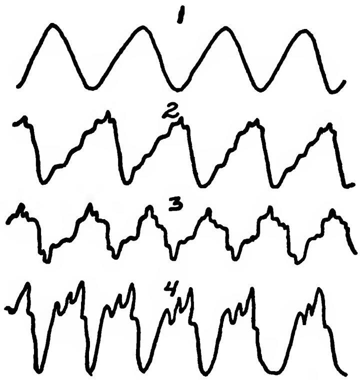
The vibrations are generated in some instruments (flute, cornet, French horn, bugle) by the vibrations of the performer's lips on a simple tubular mouthpiece. In other instruments (clarinet, oboe, saxophone) the vibrations originate in a fluttering reed placed in the mouthpiece. The reeds are flexible and they take on the natural frequency of the air column.



Origin of vibrations in various wind instruments: air jet of an organ pipe; reed of a clarinet or saxophone; lips on a cornet or bugle.

The quality of the sound is controlled by the shape of the tube and the mouthpiece, and, to some extent in any given instrument, by the manner of blowing. The higher overtones are strong in most wind instruments—particularly in those instruments where the tubes are of complicated design. The bell-shaped horn that is a feature of many instruments also helps to modify the tone. A wide, spreading bell (bass horn, French horn) tends to make the tone smooth; while a small bell (cornet, trombone) gives a sharp, brilliant quality.

Many of the brass instruments—particularly the horns—have very few keys; that is, there are only a few possible variations in the length of the air column. The bugle has no keys at all. It would seem offhand that an instrument like the bugle could sound only



Why the musical qualities of instruments differ: waves emitted by (1) a tuning fork, (2) a violin, (3) a clarinet, (4) a saxophone, all sounding the same fundamental note.

one fundamental note. But by proper variations in blowing, any desired note within a limited range can be attained. The higher notes are reached by harder blowing.

VIII. *How Are Voice Sounds Generated?*

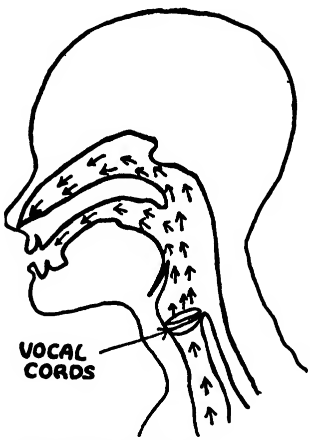
Certainly, to each of us, the most important of all sounds is his own voice. The voice apparatus consists of a bellows (the lungs) which supplies a stream of air; the vocal cords (a pair of muscular lips in the larynx or Adam's apple) which vibrate and determine the fundamental frequency; and the throat, mouth, and nasal passages, which determine to a great extent the quality of the sound emitted.

The exact manner in which all of these factors operate to produce speech sounds is very complicated, and some aspects are not clearly understood. The speech sounds themselves are exceedingly complex—as you know if you have ever seen your "voice" projected on a screen at any of the numerous scientific exhibitions where the apparatus has been available.

In this experiment, a moving beam of light traces graphically on a screen the pressure variations produced by the sound as it impinges on a microphone. By means of electrical apparatus, the fluctuations

in the microphone current are transformed into vertical deflections of a beam of light moving horizontally across the screen.

The vocal cords of each individual have their own natural fundamental frequency. In the bass male voice, this frequency may be as low as 100 vibrations per second. A woman's soprano voice may run as high as 3000 v.p.s. But in addition to the fundamental note, overtones of considerable intensity are always present. It is the relative intensity of particular overtones that distinguishes the various vowel sounds. For example, the broad *a* (as in *father*) has a maximum intensity in the frequency range of 1,000 to 1,500 v.p.s. The long *e* (as in *see*) is more complicated, with one maximum intensity



The human voice mechanism.

in the neighborhood of 500 v.p.s. and another at 3,000 v.p.s. Approximately the same frequencies will be found in both the male and female voices. The necessary overtones are brought out in some manner, not completely explained, by the way the speaker holds his mouth and operates his vocal cords.

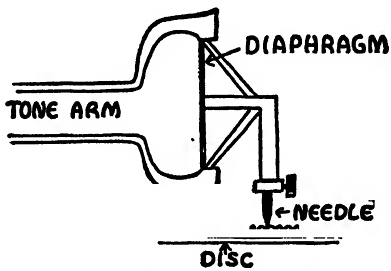
Consonants are produced when some portion of the speech apparatus partially obstructs the flow of air. Some of the consonants are produced by explosive puffs (*p, b, t*); some are nasal sounds (*m, n*); others are hissing sounds (*f, s, z*). Some consonants are *voiceless* in that they do not involve the vocal cords (*f, s, t*); others require vibration of the vocal cords (*g, m, v*). In any case, the way you hold your mouth and your lips and your tongue is the important

factor in differentiating one consonant from another—as you can test for yourself by trial.

IX. *How Does a Phonograph Reproduce Sound?*

The invention of the phonograph by Thomas A. Edison was one of the more spectacular achievements of our inventive age. Perhaps you understand already how the phonograph works, but here is a brief description.

When a recording is made, the sound vibrations from voices or instruments impinge on a microphone, where they are transformed into variations of an electric current. By means of an electromagnetic device, these electrical pulsations are in turn transformed into mechanical vibrations of a sharp needle. The needle cuts either a



Essentials of the phonograph reproducer. Vibrations of the needle in the wavy groove of the rotating disc are transmitted to the flexible diaphragm, which in turn sets up sound waves in the air.

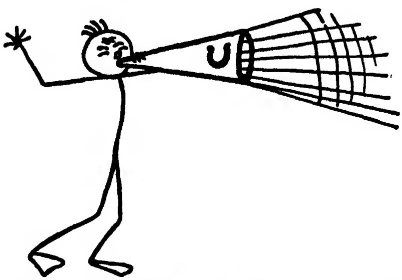
hill-and-dale or lateral wavy record of the vibrations into the groove of a wax disc. Hence, on this disc, the wavy structure of the groove follows faithfully the form of the original sound vibrations.

If copies of the recording are desired, a metal master disc is made by electroplating the wax recording disc. Reproducing records are then obtained in any desired quantity by making imprints of the master disc on a plastic material. These impressions are the records that you buy in the music store.

When a needle connected to a diaphragm in your phonograph passes along the groove of a record, the waves in the groove cause a motion of the diaphragm. This in turn sets the air into vibration and thus reproduces the original sound. The feeble sound emitted by the diaphragm is amplified, either by means of a horn, or by electrical amplifiers similar to those in a radio.

The "tone," or the fidelity with which music is reproduced by a phonograph, depends on how closely the original vibrations are duplicated. It is not very difficult to reproduce accurately a limited range of frequencies—say, from 100 to 3,000 vibrations per second. But this is not enough. For high-quality reproduction of music, a range of at least 30 to 5,000 v.p.s. is needed. Otherwise, the low notes will be missing, and the lack of high overtones will alter the quality of the instruments. The sound engineer's most difficult problem has been the prevention of distortion (that is, undue emphasis on certain frequencies); but the best phonographs and radios now give quite faithful reproduction over the necessary wide range of frequencies.

In more modern phonographs, the sound amplification is electrical, and a loud speaker gives sufficient volume without the aid of a horn. But before the days of electrical amplification, the horn was a very important part of every phonograph; and on the design of the horn depended the good or bad tone of the instrument. Even today the difficulty in good reproduction lies not in the electrical



A megaphone increases the volume of air set into vibration by the speaker's vocal organs, and also helps to direct the emitted sound.

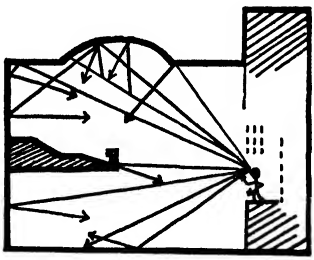
end but in getting mechanical diaphragms and horns that reproduce the sound without modifying it by their own characteristics.

The reason why the addition of a horn increases the volume of sound coming from the phonograph is not immediately obvious, but the explanation is simple enough. Without a horn attached to the diaphragm only a small mass of air in the immediate neighborhood of the diaphragm would be set into vibration. The sound would therefore be faint. But with the horn in place, the entire mass of air contained in the horn must be set into motion. A greater amount of energy is thus supplied by the diaphragm, and a louder sound is produced.

A megaphone acts much like a phonograph horn. It is true that part of the effectiveness of the megaphone is due to the fact that it helps to direct the sound; but it is also true that more energy is required to speak into a megaphone than into the open air. In other words, a larger mass of air is set into vibration when a supplementary megaphone is added to the natural megaphone formed by the mouth and throat of the speaker.

X. *What Determines the Acoustics of a Room?*

We have all had the experience of attending a lecture or other speaking performance where it was necessary to strain our ears in order to make out what the speaker was saying. This difficulty was not necessarily due to a weak voice or to poor enunciation on the part of the speaker. Rather, it may have been caused by the poor acoustics of the hall or auditorium.



Auditorium with poor acoustics: excessive reverberation (echoing) and focusing of sound handicaps the speaker.

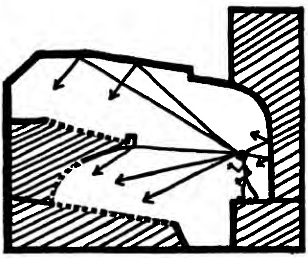
Today, the science of acoustics has been developed to such a point that there is no excuse for any new auditorium to turn out badly. The designer can calculate ahead of time just exactly what the acoustic properties of his hall will be.

First of all, large curved surfaces must be eliminated, since these tend to focus the sound reflected from them,* and thus produce local variations in intensity. Some reflection is desirable; and reflection may be put to work effectively to increase the intensity of the sound at the back of the auditorium. But in most cases, the reflecting wall and ceiling surfaces should be flat, and should be so arranged that the sound waves are reflected evenly and in the desired directions.

* In outdoor theatres and bowls large curved reflectors placed behind the performers are desirable in order to throw the sound in the direction of the audience, and also to remedy the "dead" effect due to lack of reverberation outdoors.

Probably the most common fault in auditorium design is not, however, poorly arranged reflecting surfaces; rather, it is too much reflection. Excessive *reverberation,* or repeated echoing of the sound waves from walls and ceiling, is very bad for hearing. In some halls, audible reverberations will continue for several seconds after the source of sound has been cut off. This means that a speaker must begin a new syllable before the sound from the preceding syllable has died out. The resulting confusion of sounds is what we normally term "bad acoustics."

Excessive reverberation can be prevented by providing plenty of wall surface that is effective in absorbing the larger part of the sound instead of reflecting it. Any hard surface like sheet metal, plaster, varnished wood, and the like is a good reflector; that is, it reflects



Auditorium with good acoustics: reflecting surfaces throw sound into the rear, but absorbing surfaces (dotted lines) prevent excessive reverberation.

most of the sound and absorbs (or transmits) very little. On the other hand, soft surfaces such as heavy velvet draperies, heavy carpets, and some kinds of composition wallboard are effective absorbers. These materials reflect comparatively little sound. The percentage of sound absorbed and the percentage reflected has been measured for most common materials; and formulas have been worked out which give the *reverberation time* (the time in seconds for the loudness to drop 60 decibels) for any hall, if the area of the walls and their composition is known.

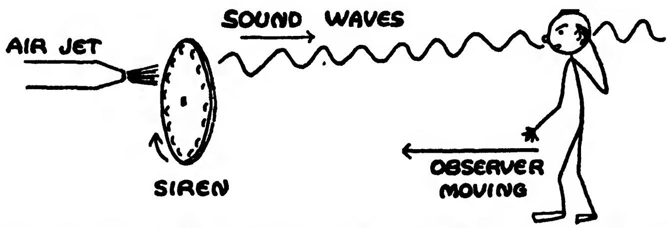
Incidentally, the audience itself is a very effective agent in absorbing sound and thus reducing the reverberation time. This means that the acoustics of an auditorium are usually much better when the seats are filled with people than when they are empty.

The optimal reverberation time varies somewhat, depending on the use to which the hall is to be put, and also on the size of the room. A longer reverberation time is needed for large rooms than for small

rooms. When the hall is to be used for speech, the reverberation time should be less than one second. Musicians, on the other hand, need a persistence of echoing in order that they may blend each note in with the others. Nor is reverberation unpleasant for the audience listening to the music. If the reverberation time is too short, the music sounds "dead." For large halls devoted to music alone, a reverberation time of 2 to 3 seconds is not too long. In any case, if the performers are to do their best, reflecting surfaces should be provided above, below, and on both sides of the stage. For halls that must be used for a variety of purposes, a reverberation time of a little more than one second is usually considered to be the best compromise.

XI. *What Is the Doppler Effect?*

We must not leave the subject of sound without discussing one more common phenomenon. Have you ever noticed that a train



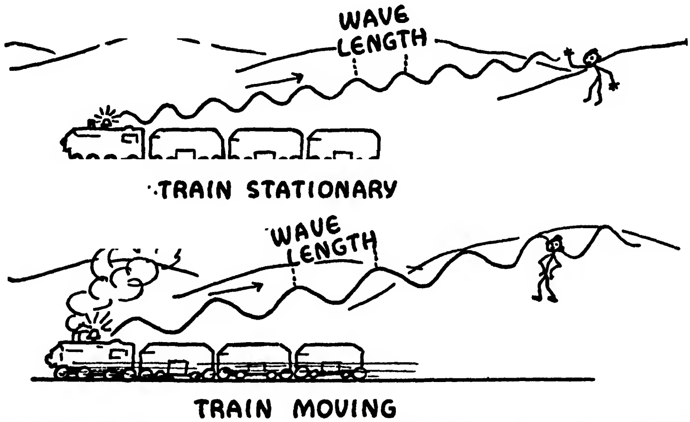
The Doppler Effect (observer moving). As the observer approaches the siren, more waves pass him each second than if he were standing still; the pitch is therefore higher.

whistle sounds higher pitched when the train is coming toward you than when it is going away? Or, have you ever remarked about the sudden lowering of pitch of the siren or bell just as a fire engine goes screaming past you? Essentially the same effect is heard if the source of sound is standing still and you yourself approach it or recede from it. This change of pitch with relative motion of the source of sound and the observer is called the *Doppler Effect.*

In order to understand the Doppler Effect, let us use water waves for the purpose of illustration. Imagine yourself in a boat traveling against the waves; that is, toward their source. It is evident that you would be crossing more waves each second than you would if you just stood still and waited for the waves to go past. Crossing more waves per second is equivalent to an increased frequency; or, in the case of sound, to a higher pitch. If, on the other hand, you

are moving with the waves away from their source, fewer waves will pass you each second; hence a lowering of frequency or pitch.

So much for the case where the source of the waves is standing still, while the observer is moving. Now, consider the observer to be standing still and the source to be approaching him. While emitting one wave, the source itself moves forward a certain distance depending on its velocity. Therefore, each wave is crowded into a smaller space than it would be if the source were standing still. The shorter wave length is interpreted by the observer as a higher frequency or pitch. Similarly, if the source is receding from the observer, the emitted wave length is increased, and the pitch is lowered.



Doppler Effect (source moving). Waves coming from the train moving *away* from the observer are of longer wave length, and are therefore of lower pitch than are those from the stationary train.

Thus, although the result is much the same whether the source is moving or the observer is moving, the explanations of the two Doppler Effects are quite different. When the observer is moving, he simply crosses more (or fewer) waves each second. When the source is moving, there is an actual decrease (or increase) of the emitted wave length.

The Doppler Effect is not limited to sound waves or to water waves. It is observed with all kinds of wave motion. In the case of light, for instance, if the source and the observer are moving away from each other, the wave length is increased, and the spectrum is shifted toward the red. Now, the velocity of light is so great

(186,000 miles per second) that ordinary speeds do not appreciably alter the color of a source of light. But most of the distant stars appear to be receding from the earth at a speed of many miles per second. At any rate, the observed shift in their spectra toward the red would indicate such a motion. This famous *red shift*, as it is called, has given rise to the idea that the universe may be expanding or blowing up.

Probably you will never have an opportunity to observe the Doppler Effect for light waves. But if you have never been aware of the phenomenon in the case of sound, listen, next time a whistling train or an automobile sounding its horn passes you—or you pass it. If, for example, a train is going 50 miles per hour, the pitch of its whistle will be almost a whole musical note higher when the train is coming toward you than when the train is going away from you.

CHAPTER TWELVE

ELECTRICITY AND RADIATION

I. *How Does the Electric Eye Work?*

We have now virtually finished our discussion of physical phenomena that occur of themselves in nature. But the wonders of modern science have made commonplace many things that nature seldom or never exhibits of her own accord. At least, such useful things as radio waves, x-rays, and the photoelectric effect were never detected until some scientist happened to assemble exactly the right combination of instruments and gadgets in his laboratory. Often, that scientist was investigating something entirely different when he stumbled on his great discovery.

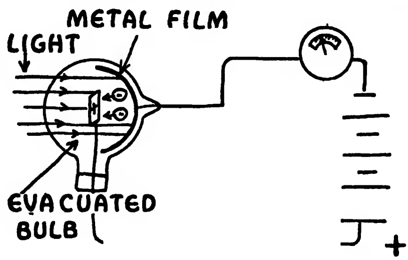
Many of the recent developments involve a combination of electricity and radiation; that is, either the conversion of radiation into an electric current, or inversely, the conversion of electric energy into radiation.

A case in point is the *photoelectric effect,* wherein light energy is transformed into an electric current: under certain conditions, light shining on a metal plate will eject electrons out of the metal into free space. If the illuminated metal plate is attached to the negative pole of a battery, and another nearby metal electrode is attached to the positive pole of the battery, the ejected electrons will flow through the air from the negative to the positive plate. The current thus generated will vary with the intensity of the light shining on the negative plate. This photoelectric effect is the basis of the *electric eye,* a device that had found wide application in recent years.

Not all light is capable of ejecting electrons from all metal surfaces. In the case of common metals like copper, zinc, and iron, only the high-energy photons of the short wave length ultra-violet radiation possess enough energy to tear electrons away from the metal. Visible light is not effective. On the other hand, the alkali metals—sodium, potassium, caesium—are more sensitive, and exhibit the photoelectric effect when illuminated by visible light, or even by the invisible long wave length infra-red radiation. Since these alkali

metals are attacked and oxidized by air, and since a gas hinders the flow of electrons across to the positive plate, the sensitive photoelectric surface must be enclosed in an evacuated bulb—hence, I suppose, one reason for the term *electric eye.*

In many practical applications, such as automatically closing doors, turning on drinking fountains, and the like, an element of mystery is introduced by operating the photoelectric cells with invisible radiation. This black light may be ultra-violet, but it is usually infra-red radiation which shines on a specially sensitized sur-



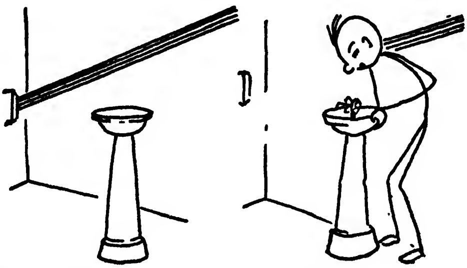
The photoelectric effect. In the electric eye, electrons are ejected from a metal surface by a beam of light.

face made up of caesium, caesium oxide, and silver. In most cases, the photoelectric currents are limited to a few millionths of an ampere, and must be amplified by vacuum tube equipment before they will perform any useful task.

Let us see how the electric eye accomplishes a mechanical operation such as turning on a fountain at the instant a person leans over to get a drink of water. A beam of infra-red light shines across the top of the fountain. The beam maintains a small electric current in the photocell circuit; and as long as this current is flowing, the water in the fountain remains turned off. When a person leans over to get a drink, his head intercepts the beam of infra-red, and the current ceases. The stoppage of this tiny current is sufficient, with the aid of amplifying equipment, to actuate a switching device which starts the water to flowing in the fountain.

In the manner just outlined, an electric eye may be made to perform any sort of mechanical task that is to follow immediately after the interception of a beam of light. Opening doors, setting off burglar alarms, accurately timing automobiles on speed trials, counting the number of people passing a given spot—these are only a few of the jobs that the electric eye performs effectively.

One of the more spectacular applications of the photoelectric effect is in the reproduction of sound for talking motion pictures. No doubt you know that a *sound track* occupies one edge of every talking film. This sound track consists of alternately dark and light lines or bands running horizontally across the narrow (about 1/8 inch wide) track. The gradations in blackness correspond to the wave motion of the sounds to be reproduced. As the film passes through the projector, a sharp beam of light, focused on the sound track, is transmitted or cut off in varying degrees by the continually changing dark and light bands across the track. The flickering of the



A drinking fountain is turned on by the electric eye when a person's head intercepts a beam of infra-red radiation.

transmitted light thus follows faithfully the wave form of the sound that has been recorded on the film.*

The portion of the light transmitted through the film falls on a photoelectric cell; and, through amplifying equipment, the pulsating current generated in the cell is first magnified many-fold, then is supplied to a loud speaker. The loud speaker in its turn responds to the pulsating current by reproducing the speech or music that was originally recorded in the form of dark and light areas on the celluloid film.

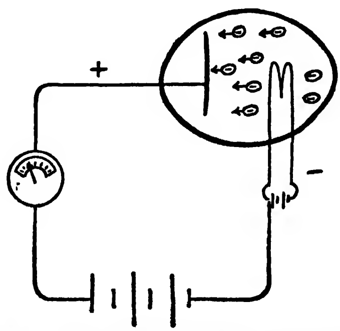
With television likely to become commonplace within the next few years, the photoelectric effect is apparently destined to add still another important achievement to its long list of successful applications. But before we see how the photoelectric effect is used in television, we must learn something of radio.

* The recording is accomplished by shining a beam of light (from a neon lamp) of varying intensity on the unexposed film. Through complicated electrical apparatus, the sound vibrations impinging on the microphone are transformed into pulsations in the intensity of the light beam. Thus, the sound track is blackened to a greater or less degree as it passes rapidly in front of the flickering beam of light.

II. *How Are Electrons "Boiled Out of Metals"?*

When, in the year 1883, Thomas A. Edison was experimenting with his newly developed "light in a bottle" (the carbon filament lamp), he chanced upon an interesting but at that time unexplainable phenomenon. He found that when he placed a positively charged metal plate inside the lamp bulb in close proximity to the white-hot filament, a current flowed through the evacuated bulb.

Later, other experimenters found that metal filaments such as tungsten exhibit the same effect—although most common metals like iron, copper, and nickel melt before they reach a temperature high enough to give appreciable current. Still later, it was discovered that tungsten impregnated with the metal thorium emits very



The thermionic effect. Electrons are driven out of the filament by heat.

much larger currents at lower temperatures than does pure tungsten. It was found, too, that filaments coated with the oxides of barium and strontium emit currents up to several amperes at comparatively low temperatures—when the filament is only a cherry red at about 1,000° C. To give a comparable current, pure tungsten must be heated white hot, to about 3,000° C. In most modern radio tubes, the filaments are either of the "thoriated" or "oxide coated" types.

We know now that electrons are the carriers of current in this phenomenon of *thermionic emission.* When the filament is heated to higher and higher temperatures, the electrons inside the metal dart hither and yon at a faster and faster rate. Finally, some of them attain sufficient energy to jump right out of the surface and escape from the strong attractive force of the metal atoms. This process is much like the escape of molecules from an evaporating liquid.

Hence, it is sometimes said that the electrons are "boiled out of the metal."

Once released by the heat, the electrons form a cloud around the filament. But if a metal plate nearby is connected to the positive terminal of a battery, while the filament itself is connected to the negative terminal of the battery, the electrons in the cloud are attracted to the plate as fast as they are emitted by the filament. Thus, the circuit is completed across a vacuum by the flow of electrons from filament to plate.

III. *What Do Vacuum Tubes Do?*

When Edison and others first observed thermionic emission, they little guessed that they had stumbled on an important and tremendously useful physical phenomenon. In fact, the names of the earlier discoverers are seldom associated with the development of radio vacuum tubes, or with the many modern applications of thermionic emission. As is so often the case in discoveries of this kind, the task of development and exploitation remained for men other than the discoverers.

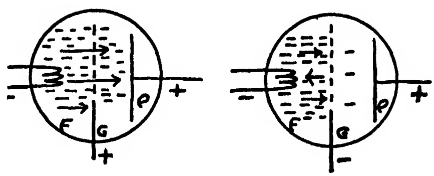
One possible application of thermionic emission early became evident. This was the rectification of alternating current: that is, the transformation of alternating current into direct current. In a vacuum tube, electrons can flow only from the filament to the plate. Therefore, current can flow in a circuit containing a thermionic tube only when the filament is charged negatively and the plate positively. No current can flow when the plate is negative and the filament positive; because, then, the electrons are attracted right back into the filament as fast as they are emitted, and there is no agent available for carrying current across the vacuum. A thermionic tube thus becomes a valve, allowing current to pass only in one direction. In the early days of radio, vacuum tubes were called *Fleming valves*, after their inventor, Sir John A. Fleming.

The use of thermionic tubes as rectifying valves is not limited to radio. A common type of battery charger, the *tungar rectifier*, employs a thermionic tube which contains a small amount of an inert gas or mercury vapor. Ionization by collision in the gas multiplies many-fold the original electron current emitted by the filament. Currents of 5 to 10 amperes are available, but only low voltages can be rectified with such a tube; otherwise, the gas will break down and conduct current in the reverse half of the cycle. If

high voltages are to be rectified, highly evacuated tubes must be substituted for the gas-filled tungar rectifier.

Besides rectification of A.C., another very important application of the thermionic tube was soon discovered; namely, amplification, or the transformation of little currents into big ones, without distortion of the shape of the current fluctuations. This application is of special value in radio transmission and reception. It has also made possible long-distance telephone communication; and it has been used for many other purposes, some of which have already been mentioned, as, for example, the amplification of photoelectric currents.

Before explaining the action of a vacuum tube as an amplifier, we must first talk about a phenomenon known as *space charge.* When electrons are emitted from a hot filament, they swarm around the filament in a cloud, like bees around a hive. Some are attracted



The amplifying effect of a three-electrode vacuum tube. (*A*) Large current flows from filament *F* to plate *P* when grid *G* is positive. (*B*) Small current flows when grid is negative.

to the positive plate; but, unless the voltage between filament and plate is very high, many of the electrons are repelled by their neighbors in the cloud, and return to the filament from which they came. Thus, the current flow is smaller than it might be if all the emitted electrons carried their charge to the plate and none returned to the filament. This swarm of electrons which cuts down the current flow because of mutual repulsion is called *space charge.*

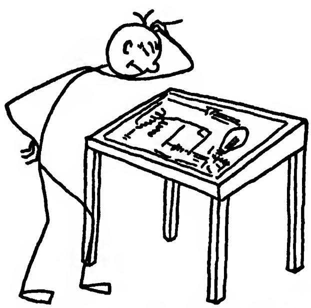
Now, suppose that a third electrode consisting of a grid or screen of fine wires is introduced into the space charge between filament and plate. Then a small positive voltage on the grid will tend to break down the repulsive effect of the electron space charge, and thus will greatly increase the flow of electrons to the plate. Although the current to the grid itself is very small (since most of the electrons fly right past the fine wires and proceed on to the plate), nevertheless the grid is very effective in controlling current flow between filament

and plate. In many tubes, a potential of only one volt applied to the grid will increase the plate current as much as will 8 or 10 volts applied to the plate. In this case, the amplification is 8- or 10-fold. The amazing ability to amplify weak signals is one of the most important of vacuum tube properties.

Vacuum tubes are very versatile. In addition to rectification of alternating currents and amplification, they are essential for one other purpose in modern radio telephony and broadcasting. This is the generation of steady, undamped electrical oscillations; such oscillations are necessary for the transformation of electrical energy into the electromagnetic radiation that constitutes radio waves. But before explaining how vacuum tubes are used for this purpose, I must describe a simple oscillating circuit, and tell what it does.

IV. *How Are Radio Waves Broadcast?*

In attempting to explain radio, I am doubtless assuming a difficult and complicated task. This certainly would be the case if I



The wiring diagram of a modern radio is extremely complicated.

expected that the discussion would enable you to look at the circuit diagram of a modern 10- or 15-tube radio and understand what happens in all parts of the circuit. The multitude of wires, resistances, condensers, coils, and other gadgets contained on the chassis of such a radio is almost unbelievable. Fortunately, however, we can leave these dense jungles of wire to the radio engineers, and we can still understand in principle how the radio works.

The basis of both the sending and the receiving set is the oscillating circuit, which in its simplest form consists of only two parts: a coil of wire, called an *inductance,* and a pair of metal plates attached to the ends of the coil. If the metal plates are placed parallel

to each other and are located close together, they are called a *condenser*. The plates of a condenser are separated from each other by air, waxed paper, oil, or some other insulator.

A condenser serves to store electric charges—positive charge on one plate, negative on the other. The larger the area of the plates, and the closer they are together, the greater the charge that can be stored on them for a given potential difference (voltage) across the condenser; that is, the greater the *capacitance* of the condenser.

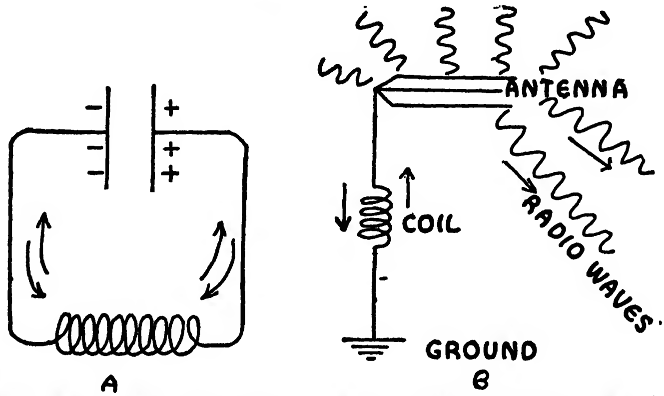
In an oscillating circuit, the charge does not long remain on the condenser. In fact, the plates may be charged and discharged well over a million times each second. In a simple circuit containing a condenser and an inductance, electrons surge back and forth, first charging one plate negatively and leaving the other plate charged positively with a deficiency of electrons; then charging the other plate negatively, leaving the first plate with a positive charge. The charge moving from one plate to the other constitutes a current, which flows through the inductance coil. Hence, a magnetic field is set up surrounding the coil. The energy contained in this magnetic field causes the charge to carry on over to the other condenser plate, much as the kinetic energy of a pendulum causes the bob to swing past its lowest equilibrium position. So, a charged condenser with its plates connected together through an inductance coil does not merely discharge itself and then remain neutral as one might expect offhand. Instead, the charge oscillates back and forth, with positive and negative charge appearing in turn on each plate.

By now perhaps you are wondering how an oscillating circuit is able to generate radio waves. A complete answer to this question lies in the realm of mathematical theory far beyond the scope of this book. But it so happens that, in any oscillating circuit, part of the energy contained in the surrounding electric and magnetic fields breaks away from the immediate neighborhood and flies out into space in the form of electromagnetic radiation. As we have noted earlier, this radiation is similar to light except that its wave length is much longer.* Like light, it travels at a speed of 186,000 miles per second. A radio signal would thus flash around the earth in less

* Though radio waves are sometimes referred to as "air waves," and radio announcers commonly talk about being "on the air," it should be evident that the air has no direct connection with radio transmission. Like light, radio waves travel most readily through empty space. The air does, however, indirectly aid in distant reception, because it provides the ionized Kennelly-Heaviside layer from which the radio waves are reflected back to earth.

than 1/7 of a second, and it would travel to the moon in slightly more than one second.

An oscillating circuit containing only a condenser and an inductance would not make a very satisfactory broadcasting station. In the first place, if the plates of the condenser are close together, very little energy is radiated in the form of electromagnetic waves. Emission of radio waves is accomplished much more effectively if the plates are spread far apart—better yet if one plate is the earth,



The essentials of an oscillating circuit. (*A*) Condenser and inductance coil. (*B*) Condenser plates spread out in form of antenna and ground increases the radiation of radio waves.

and the other plate a wire antenna or aerial located high in the air. Thus, an essential feature of every radio broadcasting station (and for that matter, of every receiver) is the aerial and ground (constituting the two plates of the condenser) connected together by an inductance coil. This is the oscillating circuit that emits radio waves.

But such a simple broadcasting station still would not be of much practical use. Oscillations once set up in the circuit would soon die out because the available energy would be rapidly dissipated. Part of the energy would go into heating the wires, and part into the emitted electromagnetic radiation. Consequently, some means must be provided for setting up and maintaining the oscillations—that is, for continually supplying additional energy to the oscillating circuit. This is where vacuum tubes enter the picture. At each surge of the charge, the trigger action of the grid of a vacuum tube sets the current flowing momentarily to the plate of the tube. Through aux-

iliary circuits, this current serves to recharge the condenser of the sending circuit to its full potential; in other words, to replenish during each oscillation the energy lost as heat and radiation.

The frequency of an oscillating circuit (and hence the frequency of the emitted radio waves) depends on two factors: first, the size or *capacitance* of the condenser, and second, the size or *inductance* of the coil. The greater the capacitance or inductance in the circuit the slower the electrons oscillate, and hence the lower the frequency.

In a typical radio circuit, the frequency might be one million cycles, or 1,000 kilocycles (one kilocycle equals 1,000 cycles) per second. In order to find the wave length of the emitted radiation, we must use the same formula as for sound waves: $L = V/F$, where L is the wave length, V the velocity of the waves, and F the frequency. For radio waves $V = 300{,}000$ kilometers per second (186,000 miles per second). Therefore, if $F = 1{,}000$ kilocycles,

$$L = \frac{300{,}000}{1{,}000} = 300 \text{ meters.}$$

By this formula you can transform the frequency scale on your radio dial to wave length, or vice versa. But first be sure that your dial reads either in kilocycles or in meters. If, for instance, the figures on the dial range from 55 to 170, they must be multiplied by 10 to give the frequency in kilocycles.

Wireless telegraphy, used largely by ships at sea, employs waves varying in length from several miles down to about ¼ mile. Radio broadcasting waves vary from a length of 1,700 feet (550 meters) down to 600 feet (200 meters). The short waves reserved for police calls, amateur communication, and foreign broadcasting vary from a length of 600 feet down to 40 feet (13 meters).

Short-wave broadcasts are frequently received at great distances from the sending station, because the short waves are effectively reflected from the ionized Kennelly-Heaviside layer, 50 to 100 miles up in the atmosphere. As a result of repeated reflections back and forth between the ionized layer and the ground, or between different strata in the ionized layer, the short waves tend to follow the curvature of the earth. In fact, such waves sometimes completely encircle the earth, and are received again at the station from which they started.

Waves shorter than 13 meters in length can be generated. In fact, radio waves less than one centimeter in length, and no different from the heat waves radiated from your stove, have been studied.

Waves 3 to 6 meters in length (frequency, 100 to 50 megacycles) are now being put to work carrying television signals and the new static-free, frequency-modulated radio broadcasts.

Another important use for short radio waves appeared in the recent war, in the application known as *radar*. We shall see in the next Chapter just what radar is and how it is useful, but a little preview is perhaps in order here.

Like visible light, short radio waves are readily reflected from objects such as the ground, buildings, and aeroplanes. Furthermore, it is possible to focus the very short waves into a narrow beam of radiation, like a searchlight beam. By sending out a brief pulse of waves in such a beam, and looking for reflections, distant objects such as approaching enemy aircraft can be detected. If the time the pulse takes to get to the object and back is measured, the distance to the object can be determined.

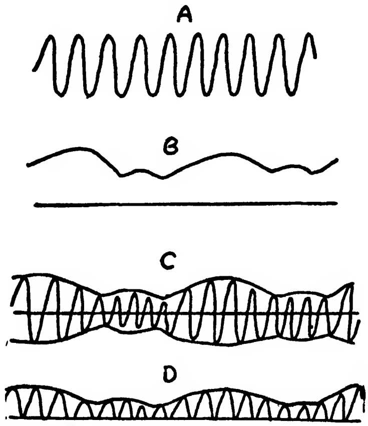
Radar was first used to give early warning of the approach of enemy bombers. As the methods became more refined, many other uses appeared. By the end of the war, radar was being employed for navigation, for blind bombing, for submarine search, for directing offensive air actions, for blind landings, and for controlling anti-aircraft guns—to mention only a few of the roles filled by this versatile military tool. Soon after the war ended, a radar signal was reflected from the moon and received back at the sending station. Other peacetime applications for radar, less spectacular than exploration into outer space, but probably more generally useful, are now being found.

V. *How Are Radio Waves Received?*

Up to this point, we have discussed chiefly the generation of radio waves, and have said little about the receiving end. Fundamentally, the receiving circuit is no different from the sending circuit. It must contain an inductance coil and a condenser. When oscillations are set up in such a circuit, radio waves are emitted; inversely, when radio waves impinge on such a circuit, electrical oscillations are generated. In order to capture as much energy as possible, the plates of the condenser are spread out in the form of antenna and ground.

In general, the oscillations induced in the receiving circuit are very feeble. But when the circuit is *tuned* properly, they become much more intense. The process of tuning consists in altering the capacitance, or the inductance, or both, until the receiving circuit has the same natural frequency as the sending station.

Oscillations having been set up in the receiving circuit by tuning, the current is first rectified, and amplified by the vacuum tubes, and then is fed into the loud speaker. The frequency of the radio-wave oscillations is much too great for the vibrating cone of the loud speaker to follow. In any case, the frequency of this *carrier* wave is far above the audible sound range. Consequently, the sound is reproduced by fluctuations in the amplitude of the radio wave oscillations. This variation of amplitude (called modulation) follows



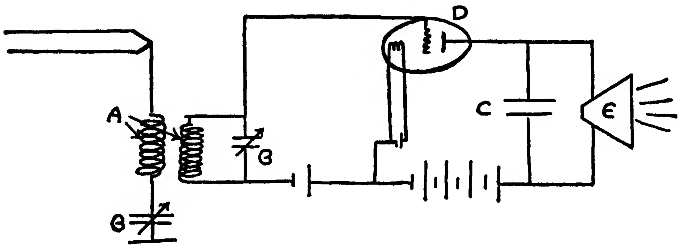
Modulation. (*A*) Undamped high-frequency radio wave. (*B*) Speech wave. (*C*) Radio wave modulated by speech wave. (*D*) Rectified, modulated wave fed to loud speaker.

faithfully the wave pattern of the words or music that impinged on the microphone in the broadcasting station. In other words, the radio waves sent out by the broadcasting station are of a single frequency, but are not constant in intensity; they fluctuate in accordance with the wave-form of the sounds that are to be reproduced.

In actual practice, there are many possible variations in the design of radio receiving circuits. One of the most sensitive and widely used types of circuit is called the *superheterodyne*. This contains a local oscillating circuit with frequency slightly different from the frequency of the incoming waves. The two oscillations (one received from the outside, the other generated in the receiver) interfere and produce beats which are of relatively low frequency and can be amplified with less distortion than can the incoming high frequency oscillations. The "squealing" that used to occur so fre-

quently in the process of tuning the old-fashioned "superhets" was caused by these beats when they were produced in the audible range. Nowadays, this difficulty is largely eliminated by automatically keeping the two frequencies far enough part so the beats are well above the audible range.

No discussion of radio would be complete without adding a word about some of its principal defects. Perhaps the most annoying of all these is static. Atmospheric static consists of radio waves resulting from lightning or some other oscillating spark discharge in the air. Man-made static is caused by the sparking of motors, by sparks passing between trolleys and wires of streetcars, and by oscillations



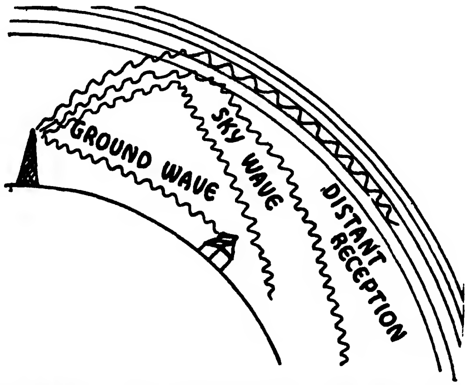
Simple radio receiving circuit using one triode tube. (*A*) Inductance coils. (*B*) Variable condensers. (*C*) Fixed condenser. (*D*) Three-electrode vacuum tube (triode). (*E*) Loud speaker.

set up in other electrical devices and power lines. On account of the quick variations in intensity of the oscillations, the static sounds generated in the loud speaker are sharp and crackling and are therefore especially disagreeable.

Nowadays, static can be nearly eliminated by using the newly developed scheme known as *frequency modulation*. In this F-M method, the amplitude of the carrier waves remains constant, but the frequency changes in accordance with the vibrations of the sounds that are to be reproduced. Since the frequency of the radio waves that cause static varies less than their amplitude, static sounds are greatly reduced. Special F-M sets that will receive the frequency-modulated waves are now on the market. Because a wide frequency band is needed for any one F-M broadcasting station, very short waves with reception limited to 50 miles or so are being called into service in order to make room for all the stations.

A second shortcoming of radio is the phenomenon known as "fading." The intensity of the radio waves from a distant station

often fluctuates in an unpredictable, though not entirely unexplained, fashion. One portion of the wave emitted by the broadcasting station comes directly to your receiving antenna. This is called the *ground wave.* A second portion may first be reflected from the



Reception of radio waves. The ionized Kennelly-Heaviside layer acts as a mirror and reflects radio waves back to earth. Multiple reflections make possible distant reception far beyond the horizon.

ionized layer 50 miles or so up in the air, then return to your antenna from the sky. This is called the *sky wave.* At certain distances from the station, the sky wave and the ground wave tend to interfere with each other. Destructive interference causes a "dead spot," or place where the signals are weak. Because of changing conditions in the ionized layer, the sky wave is somewhat irregular in intensity at any one point on the earth. This results in fluctuations in the signal strength received by your antenna. Fading is partially eliminated in modern radios by "automatic volume control." This device automatically changes the amplification as the strength of the incoming signal waxes and wanes.

During recent years, particularly, another annoyance has appeared in many parts of the United States. Generally, reception of distant stations improves at night because of changes in the ionized layer. But in order to make room for all the broadcasting stations that wish to operate, several stations must be assigned to a single frequency. Consequently, at night, when reception should be the best, two or more stations often come in simultaneously on your receiver, and thus both broadcasts are spoiled. Except perhaps in the neighborhood of large cities, nighttime reception is often limited

to a few powerful *clear-channel* stations that have a single frequency all their own.

VI. *How Is Television Accomplished?*

With television broadcasts regularly scheduled, and with commercial sets for the home now on sale, you might like to have some idea how the modern miracle of transmitting pictures by radio is accomplished.

Let us see first what happens at the transmitting end. In one standard method, an image of the picture or scene to be telecast is focused by a lens onto a sensitive photoelectric screen contained in a complicated vacuum tube called an *iconoscope*. The light-sensitive photoelectric screen is of a very odd type. By a special process of manufacture, the surface is broken up into millions of tiny separate areas, each deposited on a minute globule of silver. Each area is electrically insulated from its neighbors and also from the metal plate on which the silver globules are deposited. The iconoscope is the electrical counterpart of the human eye, with the photoelectric surface corresponding to the retina of the eye and with the mosaic pattern of the screen corresponding to the nerve endings on the retina.

As the picture image falls on the iconoscope, electrons are ejected from the tiny photosensitive islands. Each area becomes charged positively to a greater or less degree, depending on the intensity of the light at that particular point. Thus an electrical image is recorded on the photoelectric screen, much as an image is imprinted on the nerve endings in the retina of the eye.

A beam of electrons (cathode rays) originating at a filament in another portion of the iconoscope now *scans* the picture very rapidly; that is, the beam runs back and forth over the unevenly charged surface and neutralizes the charge at every point. The motion of the electron beam is controlled by electric or magnetic fields. As the charge on the photolectric surface is neutralized, the condenser-like action of the tiny insulated islands causes pulses of current to be sent out from the metal plate backing the silver deposit. The current is relatively large when the moving electron beam sweeps across a light point on the image; that is, a point heavily charged. The current is small when the electron beam sweeps over a dark point. Thus, the relative brightness of each point on the picture is indicated by the magnitude of the current. This fluctuating current

is transformed into radio-wave pulses, just as are the currents generated in a microphone by sound waves. We have learned in the preceding pages how this is accomplished.

The scanning process must take place very rapidly in order that it may keep pace with the changing scene projected on the iconoscope. In fact, the electron beam sweeps across the screen several hundred times in discharging the whole surface once; and it makes these hundreds of trips back and forth in about 1/30 second. Thus, 30 separate pictures, or *frames*, are televised each second.

Now, let us see what happens at the receiving end. Here, the oscillations of fluctuating intensity set up in the receiving circuit must be transformed back into a visible picture. This is accomplished in a vacuum tube, called a *kinescope*, in which an electron beam sweeps back and forth across a fluorescent screen. The brightness of each spot on the screen depends on the intensity of the electron beam striking it. This intensity is controlled by the pulsations of the incoming radio signals. The signals are first rectified and amplified as in an ordinary radio receiver, then applied to a grid-like arrangement which controls the flow of electrons in the kinescope tube. In this way, the original scene is recreated by an electron beam which paints 30 pictures each second as it sweeps to and fro across the glowing fluorescent screen. As with motion pictures, persistence of vision blends these separate pictures to give the illusion of continuous motion.

The quality of television reproduction is excellent when there is no static interference. However, the pictures are rather small in size. One standard kinescope screen is 7 by 9 inches. The cost of the kinescope tube increases tremendously if larger pictures are desired. There is some possibility of projecting the fluorescent images onto a large screen. To do this successfully, however, the small images must be very bright; and with the present development of fluorescent materials it is scarcely practicable to attain the necessary intensity if the kinescope tube is to have a reasonably long life.

For several reasons, very short wave-length radio waves must be used for television. Like light, these waves tend to travel in straight lines. They do not follow curved paths, nor are they effectively reflected by the ionized layer in the air. The range of television stations is therefore limited to about 25 miles, or, at the outside, 50 miles. Furthermore, television programs cannot be readily transmitted from station to station by wire. Only a very expensive type

of wire, called a *coaxial cable*, will carry the signals without distortion. This fact, combined with the great expense and effort involved in preparing television programs, as well as the higher cost of television receivers, makes it unlikely that television will ever become as universal as radio. For the time being, at least, programs will be available only a few hours a day, and then only near the larger centers of population. In the years to come, technical improvements may, of course, remove these limitations.

VII. *What Are X-rays and What Do They Do?*

From the standpoint of the health of each and every one of us, there occurred a very important event in 1895: In that year, x-rays were discovered by the German physicist Roentgen. X-rays are of value for many purposes outside the realm of medicine; but it is in the diagnosis and treatment of disease that the average person is likely to have occasion to be thankful that science has made x-rays available for him to use.

But first, let us see what x-rays are, and how they are produced, and what they do.

It has been well established now for many years that x-rays are a form of electromagnetic radiation, entirely similar in nature to light and radio waves, but having a very short wave length. You recall that the wave length of visible light is in the neighborhood of 0.00005 centimeter, or 5,000 Angstrom units.* X-rays have a wave length in the neighborhood of one Angstrom unit.

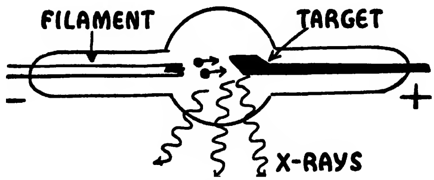
Like visible and ultra-violet light, x-rays are generated by atoms in which the electrons are disturbed from their normal positions. An x-ray photon is emitted each time an electron in an "excited" atom returns to its normal state. In the case of x-rays, the disturbed electrons lie deep inside the atoms and drastic action is required to produce excitation. Electron bullets which have been brought to tremendous speed under the action of high voltages smash into metal targets, and from these targets x-rays are emitted.

Hence, the phenomenon of x-ray emission constitutes another important example of the interaction between electricity and electromagnetic radiation. In fact, x-ray emission is a sort of inverse photoelectric effect: in the case of photoelectricity, light strikes a

* The *Angstrom* is a unit of length, equal to one one-hundred-millionth of a centimeter (10^{-8} centimeter).

metal surface and electrons are ejected; in the case of x-rays, high-speed electrons strike a metal plate and radiation is emitted.

The modern x-ray tube, developed by Dr. W. D. Coolidge, is simply a large vacuum tube containing a filament and a plate. The plate is usually called the *target.* Voltages ranging from a few thousands up as high as several million are applied between the filament and the target. Under the action of these voltages, the electrons



The Coolidge X-ray tube. X-rays are generated by the impact of high-speed electrons on a metal target. The tube is highly evacuated.

emitted by the filament attain velocities approaching the speed of light by the time they plough into the metal (usually tungsten) target. Most of the energy of the electrons is used up in heating the target but a small portion is effective in producing the penetrating x-rays that emerge through the glass walls of the tube.

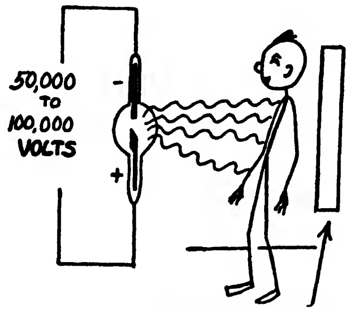
Generally speaking, the higher the voltage applied to the tube, the shorter will be the wave length of the emitted x-rays, and the more penetrating the rays will be. For most medical work, the voltages range from 50,000 to 200,000. Penetrating x-rays generated by the higher voltages are often referred to as "hard" x-rays; while the less penetrating rays generated by low voltages are termed "soft" x-rays.

Let us see now what properties of the x-rays make them useful. In the first place, the rays will penetrate materials that are entirely opaque to visible or to ultra-violet light. There is no great mystery about this penetrating power. Visible light happens to be strongly absorbed by such things as metals, wood, and bodily tissue; while it it transmitted readily through glass and air. X-rays, on the other hand, penetrate to some extent the materials that strongly absorb visible light; but the x-rays are absorbed completely by an inch or less of glass—or by a few feet, or at the most a few yards, of air.

X-rays blacken a photographic film or plate, and they cause a fluorescent screen to glow. Since bones and metals absorb x-rays more readily than does flesh, it early became evident that the newly

discovered x-rays would constitute a powerful agent for the diagnosis of broken bones or of any other internal ailment where different densities of the organ would make possible a shadow photograph. On such a photographic negative, bones, bits of metal, and other dense objects appear as light spots, because the x-rays do not penetrate through them to blacken the film. The less dense portions of the body appear black on the negative.

It would be convenient if x-ray pictures could be focused onto a small area of film as is done with visible light in a camera. However, x-rays are not appreciably refracted (bent) by glass or any other kind of lens. Therefore, it is necessary to take full-size shadow



X-ray photographs. X-rays penetrate the body of the subject and produce a shadow picture on the photographic plate.

pictures, with the x-rays shining through the subject and striking the film directly. Even with this limitation, x-rays have been of incalculable value in diagnosing such ailments as tuberculosis, gastric ulcers, tumors, and, of course, broken or displaced bones of any kind. Where some of the detail of a full-size x-ray shadowgraph can be sacrificed, however, it is possible to make small-size photographs. The x-rays make their pattern of light-and-dark on a fluorescent screen, like the screen you may have seen in the x-ray machine at your shoe-dealers', and this pattern is then recorded on film by a camera. The fluorescent screen is quite dim, so the camera must have a fast lens and must use very sensitive film. Cameras and films suitable for this purpose were not available until the past few years. The trouble, of course, is that the patient must not be exposed to the x-rays too long. The camera and film have to get the picture before the patient is in danger of injury from the radiation.

During the recent war, the use of x-rays for inspecting parts for aeroplanes, tanks, and other military equipment grew enormously. Internal cracks or blowholes might go unsuspected until they led to sudden and disastrous breakage; or much time might be wasted in machining a casting, only to find that it contained a fault. X-ray inspection is a quick and reliable method for locating such hidden flaws without harming the specimen. Perhaps you recall, too, that x-rays were used to check whether artillery shells had their full loading of explosive charge, and whether all the parts of complicated fuses had actually been put into their places.

The apparatus and techniques that were developed for the inspection of wartime production are undoubtedly going to be widely used for the same purpose in peactime, and our machinery will be that much more certain against sudden failure. X-ray inspection, even before the war, was coming into very general use—for example, perhaps you have had the tires on your own car inspected with x-rays, to see if any nails were working their way through to the inner tube.

Another important property of x-rays is their ability to ionize the air or other material through which they pass. The ionization produced in bodily tissue has important biological consequences. In the first place, prolonged exposure to x-rays (particularly the soft, long wave-length rays) causes severe burns that are very difficult to heal. Therefore the time of exposure to x-rays must be carefully regulated by a competent physician, and persons who operate x-ray machines must be completely protected by lead shields and by leaded gloves and aprons. The effect of the x-rays is cumulative; so even small daily doses may add up to cause harmful results.

But, with proper precaution, the ionization produced by x-rays may be beneficial. For some reason not completely understood, the newly-formed cells found in tumors and cancerous tissue are slightly more susceptible to destruction by x-ray ionization than are the older cells of normal tissue. Tumors often melt away under repeated x-ray dosages, and cancer in the early stages can sometimes be cured, or at least held in check over long periods. For treatments of this kind it is important that hard, penetrating x-rays of short wave length be employed. It is common practice to operate the deep-therapy x-ray tubes at 200,000 volts. Physicians are still uncertain whether voltages higher than 200,000 offer enough additional curative power to warrant the great expanse of installing and operating the equipment.

For inspection purposes, however, even more penetrating x-rays are often desirable or necessary. Commercial x-ray machines have been built in which the electrons, starting from a hot wire at one end of a long evacuated tube, are speeded up by potentials as high as two million volts before they strike the metal target at the other end.

It is very hard to build x-ray tubes which will stand overall voltages higher than two or three million volts. If still more penetrating x-rays are needed, the electrons have to be speeded up in some less direct fashion than by simply letting them fly from a highly-negative filament to a target at ground potential. One ingenious solution of the problem, which has made it possible to produce electron speeds equivalent to 100 million volts, is used in the *betatron*.

The betatron resembles a transformer, in appearance and in action. It has a laminated steel core, and it has a primary winding in which flows an alternating current. This alternating current induces an alternating magnetic field in and around the steel core. In an ordinary transformer the changing magnetic field would cause a flow of electrons in the wires of the secondary winding. In the betatron, however, there is no secondary winding of wires. Instead, there is a doughnut-shaped vacuum tube, into which free electrons are injected while the magnetic field is starting to increase. As the field increases, these electrons, with no metal atoms to hinder their flight, go around faster and faster in the vacuum within the doughnut. When the magnetic field has reached its peak value the ring of whirling electrons, now going nearly as fast as light itself, is deflected to one side and strikes a metal target, generating the x-rays.

In the 100 million volt betatron the electrons make some 250,000 revolutions inside the doughnut, traveling a total distance of more than 800 miles—all in about four one-thousandths of a second. The x-rays from this machine can penetrate many inches of lead or steel, or many feet of concrete, before absorption cuts them down to a negligible intensity.

VIII. *What is Radioactivity?*

The development of the atomic bomb and the release of atomic energy have made the nucleus of the atom a familiar subject for the public. You know, of course, that nuclei were not discovered and exploited for the first time during the war years. True, man had never before succeeded in setting free the energy of nuclei on a large scale. But the study of nuclei has been going on for 50 years, and in

that 50 years atomic energy has been used on a small scale for many practical purposes. If your wristwatch has luminous hands and numbers, for example, the light that tells you the time of night is generated from atomic energy, the same sort of energy as is set free when an atomic bomb explodes.

The story of the recent startling developments in nuclear physics is to be the subject of Chapter Fourteen. As we shall see there, the old dream of the medieval alchemists has come true, and man now knows how to change one element into another. By various atom-smashing methods, nuclei can be altered in structure, and many new and interesting nuclei, not present at all in nature, can be manufactured. These new man-made nuclei are unstable, lasting for only a little while after they are made. All such nuclei are called *radioactive.*

However, some of the nuclei that occur in nature are unstable, too. These naturally radioactive nuclei were discovered and studied intensively, long before anyone knew how to make artificial radioactive nuclei. Here, we shall look briefly at some of the characteristics and some of the uses of these natural radioactive nuclei.

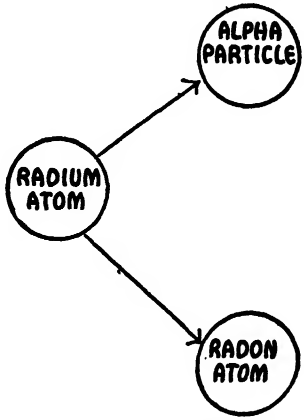
The best-known of the lot, probably, is radium. Radioactivity was discovered by Henri Becquerel in 1896. Two years later radium was first isolated, through the untiring efforts of the famous Polish woman of science, Madame Curie, aided by her French husband, Pierre Curie. The dramatic story of the Curies' early struggles and of their great triumph has been told many times, perhaps most effectively by their own daughter, Eve Curie.*

Radioactivity, in radium or in any other element, is a spontaneous release of atomic energy by a nucleus. It involves a sort of explosion in the nucleus. It can be controlled in no known way. A given radioactive nucleus may explode during the next second, or it may lie dormant for the next million years and then explode. No one knows just when it will explode, nor, for that matter, just why it does so at all. We merely know that radioactive nuclei are unstable and that on the average a certain fraction of them will disintegrate in a given period of time. It takes about 1600 years before half of the atoms in a given mass of radium explode. This period of time is called the *half-life* of the radium nucleus.

What happens when a radium nucleus disintegrates? The immediate result is a splitting up of the atom into two fragments: an

* *Madame Curie*, by Eve Curie, Doubleday, Doran, and Co., New York, 1938.

atom of the element *radon* (also called *radium emanation*), plus an *alpha particle,* which is the positively-charged nucleus of a helium atom. The process is thus one of transmutation, in which one chemical element breaks up into two entirely different elements.



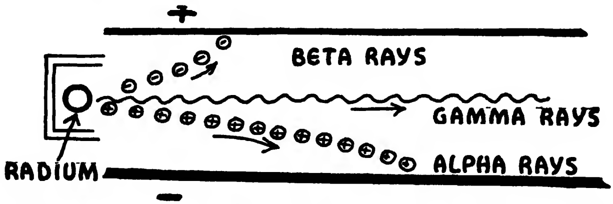
Radioactivity. The disintegration of a radium atom into an alpha particle (helium ion) and an atom of gaseous radon.

Radon is a chemically inert gas which further disintegrates within a few days into a new form of radium, *radium A.* After a lengthy series of additional radioactive transformations, radium *A* eventually turns into ordinary lead. As a matter of fact, radium itself is being formed continuously at a very slow rate by disintegration of its parent element *uranium.* Uranium, as you know, is the element that plays such a prominent role in the atomic bomb. As we shall see later, its usefulness as a source of atomic energy in large quantities depends on other properties than its natural radioactivity.

The disintegration of a uranium nucleus to form radium is thus the first step in a series of changes, which ends with the formation of lead. The successive elements in this series are all present in nature, the supply of each one being depleted continuously by radioactive disintegration and being built up continuously by disintegration of the parent element. In addition to this uranium series, two other series of radioactive elements occur in nature. One begins with the element thorium, the other with the element protoactinium. The three series, all together, include some 40 different radioactive nuclei.

During the various radioactive transformations, three types of radiation are emitted: (1) *alpha particles* which, as we have already

noted, are positively charged helium nuclei; (2) *beta particles,* which are ordinary negative electrons traveling (usually) at terrific speeds; and (3) *gamma rays,* which are not particles at all, but are like x-rays of very short wave length.



Three types of rays are produced by radioactive materials: (1) positively charged alpha particles (helium ions); (2) negative beta particles (electrons); (3) gamma rays (short electromagnetic waves). The gamma rays are not deviated by an electric field.

The alpha particles produce strong ionization by the collision process as they plough through a gas or other material; but they penetrate only a few centimeters of air before their energy is used up and they become ordinary helium atoms. A sheet of metal no thicker than a hair is sufficient to stop them. Their initial speed is in the neighborhood of 10,000 miles per second.

The beta particles start on their travels at speeds sometimes approaching the velocity of light (186,000 miles per second), and often they can penetrate a quarter-inch of aluminum or many feet of air before they slow down and become indistinguishable from ordinary electrons.

Though alpha and beta rays are of great interest to the scientist and have proved themselves useful in many types of research, they are of comparatively little value for medical purposes. Rather, it is the gamma rays with their prodigious power of penetration that are effective in treating tumors and cancers. These electromagnetic rays may penetrate several inches of lead or iron, and are absorbed only to a small extent in passing through the human body. But as in the case of hard x-rays, the portion of the radiation that is absorbed in the body is effective in producing ionization and hence in destroying malignant cells. Gamma rays can also be used instead of x-rays for inspection purposes, since they pass through opaque materials and cast a shadow-pattern on a photographic plate or film. The method is the same, whether gamma rays or x-rays are used.

In giving radium treatments, the radium itself is often applied directly. The radium (usually in a chemical compound such as radium bromide or chloride) may be contained in a small needle-

shaped tube, which is inserted into the substance of a tumor. Frequently, if the area to be treated is of wide extent, several tubes are used simultaneously.

Since only certain products of the disintegration (radium *B* and radium *C*) give off the useful gamma rays, it is not essential that the original radium be employed in treatment. Frequently, the radium is stored in a vacuum, and the gaseous radon allowed to accumulate. This gas is pumped off at intervals and is sealed into tiny glass tubes which are carried to the patient and applied as needed. Since the half-life of radon is less than 4 days, and that of the radiums *A*, *B*, and *C* only a few minutes, a radon tube remains active for only a week or so. It must then be replaced by a fresh tube.

Radium and its products of disintegration are dangerous materials unless administered in limited doses. Like x-rays, the radium rays produce severe burns. In addition, radium is a deadly poison, and if taken internally will result in slow, painful death. The effect is cumulative, and a number of workers engaged in painting luminous clock dials have been poisoned. The luminous paint contains only minute quantities of radium, but it is said that the workers were in the habit of touching their paint brushes to their tongues for the purpose of wetting the brushes. After some months, these unfortunate people received enough radium into their systems to cause a horrible death.

Incidentally, the light emitted by the luminous dial of your clock does not come directly from the radium, but is fluorescent in origin. The alpha particles produce a faint glow when they strike a fluorescent material such as zinc sulfide contained in the paint. This same self-luminous mixture is now being used to mark the dials of panel instruments in night-fighting warplanes. The pilot has to be able to read these gauges, of course, but he wants them to be very low in brightness, so that the adaptation of his eyes to the darkness around the plane will not be spoiled every time he glances at the instrument panel. In some cases, the fluorescent material alone is used for the marking, and a weak source of ultra-violet radiation is provided to excite it to emit fluorescence.

In connection with the danger of radium poisoning, a word of warning is in order about the use of mineral waters, medicines, or other quack remedies, that are alleged to be radioactive and hence beneficial. Radium in itself has no known medicinal value, and it can only prove poisonous when taken internally. Fortunately, most of the remedies advertised as radioctive actually contain little or no radium and are therefore harmless, if likewise valueless.

CHAPTER THIRTEEN

RADAR, ROCKETS, AND OTHER RECENT WONDERS

I. *What Did Physicists Do During the War?*

In this Chapter and the next we are going to have a look at some of the scientific marvels developed during the Second World War. When the first edition of this book was published in 1943 the work of perfecting these things and bringing them to bear against the enemy was in full swing. We could not talk about them then. But now that the war is over and won, such things as radar, atomic bombs, rockets and jet propulsion can be discussed fairly freely. A few of the war-born wonders are still on the secret list, of course, but we can be pretty sure that most of them have by now been disclosed.

Novel and striking as they are, the developments of the past few years do not at all upset the structure of Physics. Every one of the new discoveries is an outgrowth from knowledge that was gained by patient research in the long years before the war. Almost every one of the clever new gadgets is an application of principles that were familiar when Hitler was still an upstart agitator. If you have read carefully the twelve Chapters before this you have an excellent background for understanding the recent advances. To make it easier, we will refer now and then to the earlier Chapters where the basic principles are explained.

You will probably agree that the atomic bomb is the most exciting of all the wartime developments. When President Truman gave us the news about it over the radio, the whole country seemed to draw in its breath sharply in amazement. Some of the citizens are still holding their breaths, figuratively, in fear that the human race will harm itself beyond repair by misuse of atomic power.

The story of the atomic bomb and atomic power is a long one. Unfortunately, too, it is rather complicated. We will save all of it for the next Chapter. In this Chapter we will discuss some of the other things, such as radar and rockets, that were probably just as important as atomic energy in winning the war, but seem less likely to have a violent effect on our lives in the future.

But first let us ask about the physicists themselves. What were they doing during the war? Where and how did they work? Now that the war is over, what are their hopes and plans?

If you had taken a trip through the United States back in 1939 and had dropped in to visit every physicist you could find, you would certainly have concluded that physics is a most diversified occupation. You would have found some of the physicists in their laboratories, surrounded by a complicated maze of wires and glass tubing and meters and apparatus of all kinds. Others would have been busy with slide rules or calculating machines, figuring out the results of their experiments or theories. Still others would have been in libraries, studying the published work of other physicists or writing up their own researches for publication. Some you would have missed because they were away at meetings, discussing their ideas and findings with one another.

The physicists in 1939 were scattered all over the country, mostly in groups no larger than six or so, in colleges and universities. Each physicist was working away at whatever question seemed most interesting to him, so that the number of different things being studied was not much less than the total number of physicists. Only in a few of the larger universities and in a few industrial laboratories and research foundations would you have found large teams of physicists organized to study single problems.

The war changed all this. The knowledge and skill of the physicists and other scientists were seen to be an important national resource. These assets, it appeared, could best be used in an all-out attack on a few special developments—radar and the atomic bomb were at the top of the list—which promised to be decisive for the outcome of the war. Many of the physicists were called from their scattered places and their varied interests and were organized, along with scientists from other fields, into a few great central laboratories. There, in the greatest secrecy, they worked hard to make these new things ready for use against the enemy. How successfully the job was done you know already, at least in a general way. We are going to see, in this Chapter and the next, how they solved some of the problems.

Since the war the physicists have been turning back to their accustomed laboratories and their usual work, glad to be free from the unnatural restraint of secrecy.

But their experience with highly organized research has caused some of them to look critically at the rather haphazard way things were done before the war. The achievements of the great central laboratories, some say, prove that the most efficient way to find out about Nature is by organizing great teams to work cooperatively on certain chosen problems.

Others say no. Though the wartime laboratories were very successful in taking well-known principles and developing them into effective military tools, they added very little, these others claim, to the store of basic knowledge. There is danger, they say, that in driving along directly toward a few fixed goals we will miss even more important things along the wayside. They believe the best method is to have as many people as possible studying many different things and keeping their eyes open for unexpected happenings. They can cite an impressive list of modern developments, including x-rays, radioactivity, vacuum tubes, and even the atomic bomb itself, each of which had its beginning when someone saw something he did not expect and could not understand, and decided to stop what he had planned to do and find out more about this curious occurrence.

It is too soon yet to guess how this difference of opinion is going to be resolved. If those who want research to be well-organized and centrally planned and directed have their way, this may well turn out to be a more important result, for good or for bad, than any of the tangible products of the wartime laboratories.

It is not so hard to guess what will be the most exciting field of research in physics for the next little while. Just before the war, physicists were getting more and more interested in the *nuclei* of atoms. They had already learned much about how these atom-cores are put together and how they can be changed about or taken apart. Nearly all these studies were halted by the war, except for the work which resulted in the atomic bomb. As we shall see in the next Chapter, this work was rather specialized. It left unanswered many of the questions about nuclei that were puzzling physicists in 1939 and 1940. However, it did prove that the stored-up energy of nuclei can be set free in tremendous quantities. This result has made it obviously important, from a practical viewpoint, to find out all we can about nuclei. We can expect that nuclear research will hold the center of the stage for a time—until something more intriguing and mysterious comes along.

II. *What Is Radar?*

Once, even the word was unmentionable. Then for a while the word was public property but only the vaguest hints of what it meant were circulated. It was in this period that some wag gave out the whispered information that "radar (lean a little closer, please!) is 'radar' spelled backward."

You know by now, of course, that radar is used for detecting hostile aircraft while they are still many miles away. Perhaps you have heard of some of its other military uses: for directing the fire of anti-aircraft guns; for showing bombers the way to a target that is hidden by clouds or darkness; for helping night-fighting aircraft to find their prey; for locating submarines that have incautiously poked themselves up through the surface at night; for "seeing" enemy ships through fog or storm or darkness; and for guiding planes to a safe landing when the ceiling and visibility are zero.

Maybe you have even been told that the term "radar" is a contraction of the phrase "radio detection and ranging"; sometimes the right words are said to be "radio direction and ranging." Together, these two phrases describe, correctly and completely, what a radar set does. It uses short-wave radio to detect a distant object, to measure how far away it is, and to find out the direction toward it.

First let us see how the range is measured. Then we can go on to discuss the measurement of direction. The matter of detection will take care of itself—obviously we could not get very far with any measurement of range and direction unless we could first detect the object.

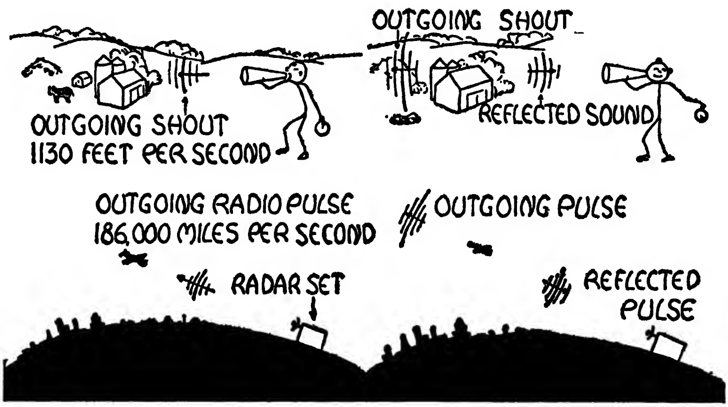
Have you ever shouted toward a cliff or a woods or a distant building, and then listened to hear your voice come back as an echo? No doubt you have—it is an experience most youngsters enjoy sometime while they are growing up. We had a little to say about echoes back in Chapter Eleven (Page 237), mentioning that they are sound waves reflected back from the distant obstacle. Now we need to look into this matter of echoes more closely, because radar is nothing more nor less than an echo-measuring business. In radar it is radio waves, instead of sound waves, that are echoed back. This difference in the sort of waves entails many other differences, of course; but essentially a radar set is quite like a boy who shouts and then puts his hand behind his ear to listen for an echo.

You remember (unless you are one of those exceptions who never heard an echo) that the sound takes a longer time to come back, the

farther away the reflecting surface is. In fact, if the time between the shout and its return is measured the distance to the reflector can be computed right away, from the fact that

$$\textit{Distance}\ (\text{feet}) = 565 \times \textit{Time}\ (\text{seconds}).$$

Roughly, if the sound returns in five seconds the echoing surface is about half a mile away. If you compare this equation with the one on Page 237 you will see that the figure 565 (feet per second) is just half the speed of sound in air. This is so because the sound has to make a round trip, to the reflecting object and back, and the time it takes is just the same as would be needed for a one-way trip at half the speed.



Range and direction can be measured by sound-pulse echoes (above) or by radio-pulse echoes (below).

With radar the situation is exactly the same, except that half the speed of *light* must be used instead of half the speed of sound—you recall that all kinds of electromagnetic waves, from the longest radio waves down to the shortest gamma rays, travel with the same speed, 186,000 miles per second. In other words, the distance from the radar set to the object that reflects the radio wave back in a certain length of time is given by

$$\textit{Distance}\ (\text{miles}) = 93{,}000 \times \textit{Time}\ (\text{seconds}).$$

We are not often interested in using radar to measure distances greater than a hundred miles or so. For such short distances, the radio waves make their round trip in a time much shorter than one second. In fact it is the practice in radar to use one millionth of a

second (one *microsecond*) as the unit of time. With this unit, the distance from the set to the reflecting object is given by

$$\textit{Distance} \text{ (miles)} = 0.093 \times \textit{Time} \text{ (microseconds)}.$$

If the wave goes out and is echoed back in 10 microseconds the reflecting object must be nearly a mile away (0.93 mile); if the round trip takes 100 microseconds the object is 9.3 miles away; if it takes 1000 microseconds—a thousandth of a second—the range is 93 miles.

To find the range, then, the radar set simply sends out a short pulse of radio waves toward the distant object and measures the tiny interval of time it takes for the pulse to get back to the set, after reflection from the object. The longer this time, the greater is the range. Since the relation between the echo-time and the range is accurately known, the time-measuring meter can be marked off with a scale of miles and the range can be read directly from it.

Did you notice that it is a *short pulse* of waves that is sent out? If you think back to the days when you listened to sound echoes from a distant cliff, perhaps you will see why the pulse needs to be short and sharp. If you blow a whistle continuously toward the reflecting surface, the weak returning wave is lost in the strong outgoing wave, and there is nothing to get hold of for measuring the round-trip time. But a sudden sharp blast on the whistle is echoed as a sudden sharp blast, and the time this brief pulse takes to go out and back can be measured accurately.

In practice, it is hard to make a radar set send out pulses much shorter than one microsecond in duration. This means that ranges shorter than about one-tenth of a mile (528 feet) cannot be measured. On the other hand, the time between the leaving of the pulse and its return can be measured with a precision of about one-tenth of a microsecond, if the object is far enough away so that the set is all finished with sending out the pulse before the echo starts coming back in. This means that the range, if it is not too short, can be measured with an uncertainty of only 50 feet or so.

We have been speaking all along as if the radar set, like the boy in front of the cliff, gave out one single shout or pulse, waited for an echo to return, and then quit entirely. Actually, the set continues to send out pulses, one after another, and gives a continuous indication of the range to any object that sends back a measurable echo.

A little later we shall see how this information is displayed. Right now, we want to decide how often the pulses can occur without causing any trouble. With a little thought you can probably

figure out the answer for yourself. Before sending out each new pulse we must allow enough time for the preceding pulse to go clear out to the extreme working range of the set, and then allow this same length of time for the echo (if there happens to be an object out there to reflect the pulse back) to return to the set. It would do no particular harm to have, at any instant, more than one pulse on its way out to the object and back, but it would be very troublesome to sort things out and match up each returning echo with the proper outgoing pulse. It is simplest to deal with only one pulse at a time.

For example, if the working range of the set is 93 miles the pulses are spaced at least 1000 microseconds apart; the number of pulses per second—the pulse repetition frequency, as it is called—is kept well below 1000. On the other hand, there is nothing to be gained by spacing the pulses much farther apart in time than this minimum. In fact, if the set waits around very long between pulses it is simply wasting time that might as well be used for getting more echo-information. So, in practice, each pulse is sent out very soon after the last echo from the preceding pulse has had time to get back to the set.

Now, how does radar find out the direction from the set to the echoing object?

Again we can think of the boy who shouts and listens for the sound echo from a distant cliff. This time we are going to give him a little problem to solve. We blindfold him tightly, turn him around a few times to confuse him, and then ask him to find out which way the cliff lies and point to it.

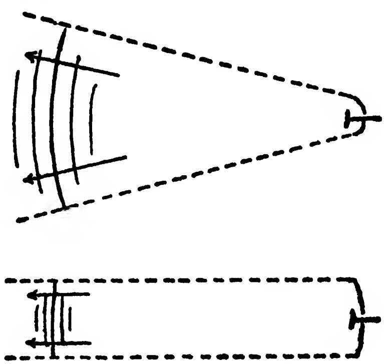
Is this too hard? Not at all, if he is a bright boy who understands how sound waves behave. He would simply cup his hands before his mouth to direct the sound straight in front of him, and would then turn around slowly, all the time shouting and listening for an echo. When the echo came back loudest, he would know that he was facing straight toward the cliff. If the boy had a long, narrow megaphone (Page 258) to concentrate the sound into a narrow beam he could solve the problem even more readily. With a little practice he could even locate such small objects as houses and silos with fair precision—especially if it occurred to him to use the megaphone for listening as well as for shouting.

In radar, this very same principle is used for finding directions. The pulse of short radio waves is concentrated into a narrow cone or beam, looking outward into space away from the set. This beam is turned around and is tilted up and down until the distant reflect-

ing object sends back its strongest echo. When this happens, the beam is pointing right toward the object.

Why does radar use *short* radio waves? Actually, there are several reasons. For one thing, the shorter waves are reflected more strongly from small objects such as aeroplanes and submarine conning towers. Long waves such as are used in radio broadcasting, with a wave length of a thousand feet or so, simply bend around such obstacles and are only slightly reflected. The shorter the wave length, the closer do the radio waves resemble ordinary light waves in their reflection properties.

Another reason for using short waves—a most important reason—is because it is relatively easy to concentrate them into a narrow



Long waves from a small antenna system (above) spread out into a wide cone; short waves from a small antenna system (below) form a narrow beam.

beam. With a narrow beam of pulses, the direction toward an echoing object can be determined very precisely, and this is obviously a good thing.

The sharpness of the beam is limited, in fact, by the size of the antenna (which is designed to send out the pulses in a certain direction, like a megaphone) relative to the length of the wave. The antenna has to be at least a few wave lengths across if the beam is to be at all sharp. If the waves are a few feet long, the antenna has to be many feet in extent, and it is hopeless to think of carrying it about on a truck or getting it aloft in an aeroplane. But if the wave length is only an inch or so, an antenna only a foot or so across will give a sharp beam, and such a small antenna can easily be mounted and handled on a truck or an aeroplane. Or, the short waves can

be used with large antennas on the ground to produce extremely narrow beams.

All during the war both sides worked hard to exploit shorter and shorter radio waves for radar use and thus make radar a more and more versatile military tool. We and our allies, fortunately, kept the advantage in this drive toward shorter wave lengths.

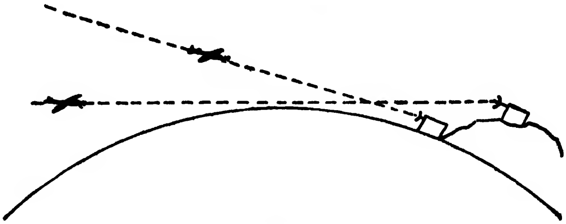
When the war started no one knew how to make strong pulses of radio waves much shorter than 10 or 15 feet. In the Battle of Britain, waves of this length, sent out across the Channel from a great chain of stations on the coast of England, gave the R.A.F. early warning of the approach of German bombers and enabled them to get their few fighter planes aloft and in position to intercept the enemy.

Soon, however, sets using waves only about two feet long were built. This is nearly as far as it is possible to go with ordinary vacuum tubes. For many months, the radar work on both sides settled down at this wave length region. Then came a great advance. A new tube of the *magnetron* type, modified to generate high frequency impulses by a design first devised by the British and then improved in this country, made it possible to get strong pulses at a wave length of only four inches (10 centimeters). Later, magnetrons were developed to give waves only a little longer than an inch (3 centimeters). Before the war ended, 10-centimeter and 3-centimeter radar sets were in wide use.

Have you been wondering what limits the working range of a radar set? It depends, of course, on the strength of the pulses sent out, on the sensitivity of the receiver that picks up the echo, and on the size and reflection properties of the object that sends the echo back. You will notice that, in these respects, radar is still quite like a boy shouting and listening for a sound-echo. But there is another limitation to the practical range of a radar set, which might not occur to you at first thought.

This other limitation comes about because the earth is curved, whereas the beam of pulses goes out from the set in a straight line. The beam is therefore higher and higher above the earth the farther it gets away from the station. Finally, the beam is so high that there is nothing of interest up there to send back an echo—no aeroplanes, no V-2s, no clouds. If you recall the radius of the earth (4,000 miles) and a little geometry, perhaps you can figure out for yourself how high above the curving earth the pulse is when it gets 100 miles away from the set. The answer, assuming that the earth is quite

round and smooth and the pulse starts out on a level path, is about $1\frac{1}{4}$ miles—anything lower than this, at a range of 100 miles, cannot be detected. You can easily see that it will help matters to put the



The radar set on the hill can "see" farther over the curved earth.

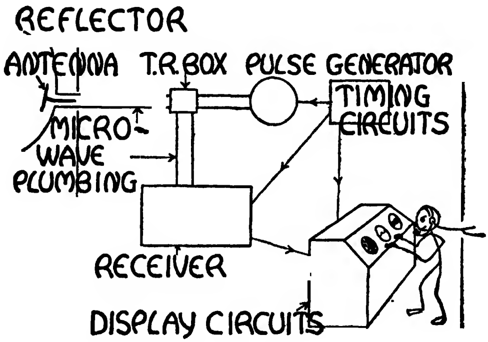
set up on a high hill so that the earth can approach the beam for a while before it starts going down and away from it. If the set is very high up, in an aeroplane, this limitation to the range is obviously much less severe. But airborne sets usually have only enough power for a working range of a few miles.

Now that we have seen how radar pulses can be used to detect, and to measure range and direction, perhaps you would like to poke about in a typical radar set and see what its parts are and how they are put together.

We might begin with the antenna. If it is one of the older radars using long waves, the antenna is likely to remind you of an enormous bedspring stood up on edge. You would notice some metal rods mounted out in front of the bedspring affair. These metal rods are the actual antenna: the radio waves start out from them and are reflected forward by the huge sheet of metal mesh. If it is a 10-centimeter or 3-centimeter radar the antenna will look rather like a dishpan, made of wire netting or thin sheet metal. Just in front of the center of the pan, on its concave side, will be a little metal rod. This rod is the actual source of the short radio waves; the pan is simply a mirror to concentrate the beam in the forward direction. You may think this is like the filament and curved reflector in your flashlight or automobile headlamp, and you will be entirely right. The two things are quite alike in form and in action. On a short-wave set the antenna might even be a simple horn, like a megaphone, though this construction is not much used. Whatever its shape, the antenna will usually be mounted so it can be turned around and around and tilted up and down.

Somewhere back of the antenna is the pulse generator, a vacuum-tube oscillator or a magnetron, with some circuits for making it give out a short pulse of radio waves every so often.

Off to one side of the generator is the sensitive receiver, which has the task of detecting the weak echoes, changing them over to a lower frequency (the heterodyne principle, described on Page 274, is used), amplifying them, and delivering them to the circuits that compute and indicate the range and direction.



The essential parts of a radar set.

It is common practice to use the same antenna for sending out the pulses and receiving the echoes. This calls for a sort of valve or switch which can be thrown one way to let the strong pulse go out without wrecking the sensitive receiver as it passes by, and can then be thrown the other way to divert the weak echo into the receiver. The switching has to be done very rapidly, of course—you remember that the set must be ready to listen for an echo within a very few millionths of a second after it sends out a pulse. It is not surprising that it is done electronically. An ingenious little device called a "T-R box" (for "transmit-receive"), somewhat like a neon lamp, does the job very satisfactorily.

If you expect that the antenna and generator and receiver are connected together by ordinary wires, you are in for a little surprise. These short radio waves simply will not travel about on ordinary wires. The longer waves such as were used in the early days of radar could be carried from place to place by coaxial cables (Page 279). But 10-centimeter and 3-centimeter waves have to be piped around (literally!) in hollow tubes of a certain shape and size to fit the wave

length. The "wiring" is called "microwave plumbing," and the radar engineers have had much to learn about the behavior of short radio waves inside these hollow guides.

Before we leave the radar set we will certainly want to see how the echo-information is finally displayed, after the receiver and the timing circuits have done their work with the returning pulses. As a matter of fact, a radar set usually has several indicators, for showing the range, direction and height separately. We can see how one of the most interesting of them works, and can then take it for granted that the radar engineers have been just as ingenious with the others.

The echoes are shown on the round flat face of a kinescope tube, of the same kind as is used for displaying television pictures (Page 278). When a pulse leaves the antenna, a very faint spot of light (caused by a very weak electron beam striking the fluorescent material on the kinescope face) starts to move outward from the center of the face toward the edge, moving along a line. Its pace across the tube matches the pace of the radar pulse out into space. If an echo comes back, the spot is brightened momentarily. The distance from the center of the tube out to this bright spot shows, of course, the range from the set to the reflecting object—in fact, the tube can be marked off with circles about its center representing ranges of five miles, ten miles, and so on out. When the moving spot reaches the edge of the tube face, corresponding to the extreme working range of the set, it is moved quickly back to the center again and is then ready to start another outward trip when the next pulse leaves the antenna. If the antenna turns around as it sends out the successive pulses, the path of the spot across the tube face is turned around at the same rate, like the hand of a clock. What the observer sees, then, is a map of the space all around the radar set, just as if he were stationed many miles up in the air over the set and could look down, even through clouds and darkness, at everything in the air below him.

III. *How Is Radar Used in War?*

Now that you know what radar is and how it works, you can probably see for yourself many ways it might be used in warfare. Some of the applications we have already mentioned. A set on the ground can give an early warning of approaching enemy aircraft. The observer watching the display tube can see all the time where friendly aeroplanes and enemy aeroplanes are located in the sky, and

can give his own pilots instructions, over the radio, for avoiding the enemy or meeting him, whichever is desired. In the same way, he can watch over a friendly bomber formation in flight and can tell the pilots how to fly to the target and how to get back home. A set mounted in an aeroplane can look forward into darkness or clouds and find the enemy, or it can look out over the surface of the sea and report on ships and submarines ahead. Mounted on shipboard, the radar set can be used to spot other vessels for miles around, or to locate landmarks such as islands and harbor entrances.

If the bomber carries along his own radar set he can find his way to the target and back without help from a ground station. Since the striking range of modern bombers is far greater than the working range of a radar set, airborne radar for navigation and blind bombing was very useful in the latter days of the war. The beam of pulses is sent downward from the aeroplane, scanning the terrain on all sides from directly below out to the horizon. If water and land and forests and cities were all alike in their ability to reflect short radio waves, the returning echoes would all be the same strength and the display tube would be uniformly bright all over. Fortunately, however, these different surfaces have different echoing properties; the display tube therefore shows a map of the terrain, even though it is hidden under clouds or darkness. The map is rather fuzzy, of course, but with practice the observer can pick out recognizable landmarks for navigation and can find the place where the bombs are to be delivered.

Radar is useful for directing anti-aircraft fire, even in daylight when the flying target can plainly be seen. The radar set measures the range and direction of the aeroplane more quickly than can be done by other methods, and thus saves valuable time in getting a shell, fuzed to explode at the proper distance, started upward in the proper direction.

The radar set can even be arranged to control the gun all by itself. For this purpose, the receiver is interconnected with the machinery that drives the antenna so that once the beam is pointed toward a flying target it automatically continues to point toward this target as the target flies along. The set is then connected with the gun, through a computing machine which figures out just where the target is, how fast it is going, how the gun should be pointed, and what the fuze setting should be. With such an automatic arrangement, once the set is "locked in" on a certain target the gun swivels

about by itself, and is ready to fire shells as fast as the crew can stick them into the automatic fuze-setter and load them into the breech. No one needs to bother his brains with any calculations, or shout any orders. It is all done electrically and mechanically.

These combinations of a radar set, a computer, and an anti-aircraft gun (or battery of several guns) were used with success against the buzz-bombs coming in over the south coast of England in 1944. As you can imagine, a buzz-bomb flying along straight at a fixed altitude is, except for its high speed, the very easiest of all flying targets to hit. A piloted aircraft could make the problem harder by taking unpredictable evasive action.

This mention of guns and shells brings to mind another very clever and effective wartime device, the so-called "proximity fuze." Perhaps the proximity fuze ought not to be classed as a radar device. But it does use an echo principle, and at any rate it is an interesting little gadget.

Packed away into a space no bigger than an ordinary tomato can, in the nose of a shell, are two complete radio sets, a transmitter and a receiver. When the shell is fired the transmitter goes into action, sending out short radio waves continuously in the forward direction. At the same time the receiver wakes up and starts listening for these waves to come back to the shell. So long as there is nothing out in front or to the sides to send back a reflection, the transmitter keeps on sending out the waves and the receiver keeps on listening. But let the shell come close enough to an unlucky aircraft to get a little echo back into the receiver, and the receiver reacts to explode the shell immediately. The sensitivity of the receiver is adjusted just so that the shell will explode when it comes into lethal range of a reflecting target. In effect, the proximity fuze makes the target much larger than it would appear to a shell equipped with an ordinary contact fuze, and therefore much easier to "hit." Also, the danger of exploding the shell before it gets within range of the target or after it has passed by, which can easily happen with a time-fuze, is avoided.

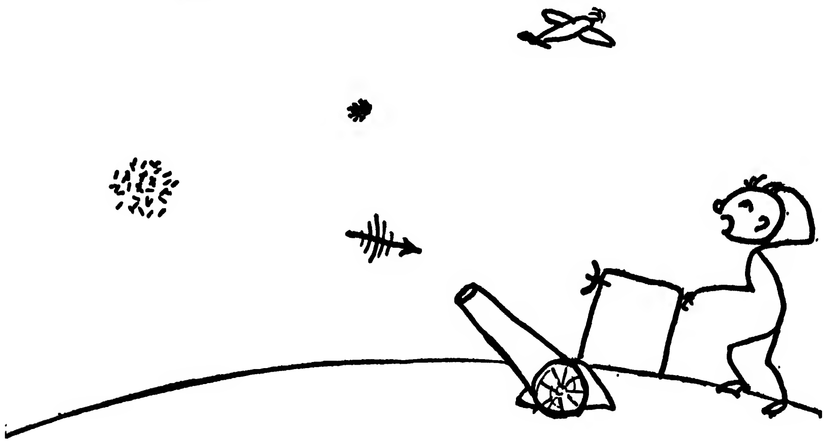
The same kind of fuze, used in a bomb or rocket intended for a ground target, will make the charge explode well above the ground and hurl the fragments downward over a large area.

IV. *How Can Radar Be Tricked?*

Every new military device calls forth an effort to nullify it. Radar, in the past war, was no exception to this rule. Along with

the feverish activity by each side to make its own radar more effective went an equally feverish search for countermeasures to the enemy's radar.

One way, of course, is simply to drown out the enemy's receivers by sending over to him a lot of meaningless and confusing signals that are stronger than the weak echoes he is listening for. This method is known as "jamming." Jamming can be done with relatively weak transmitters, much less powerful than the radar sets that are being jammed, because the jamming signal is competing only with a faint echo. The jammer can be used on the ground or carried aloft in aeroplanes, perhaps over enemy territory. To avoid the jam-



A few metal strips, cut to the proper length, give as strong a radar echo as does a big bomber.

ming (yes, there are countermeasures to the countermeasures) the enemy can change the operating wave length of his radar set a little, so that his receiver is no longer sensitive to the jamming signal. Unless the jammer can follow such changes of wave length almost as quickly as they are made, or unless the jammer is built to jam many different wave lengths at the same time, jamming can be combatted quite effectively by shifting the radar to a new operating wave length.

Another way of tricking radar is to place in the sky something that looks to the radar set like an aeroplane or a formation of aeroplanes, but is not. Maybe this sounds to you like a hard assignment. Actually, it turns out to be quite easy. All that is needed is a hand-

ful of metal strips cut to be about half a wave length long—25 centimeters (10 inches), if the set you want to deceive is working with waves 50 centimeters long. If the length is right, these strips are very effective reflectors for the waves. A few hundred of them in a scattered group will send back as large an echo as a large bomber. The length is the important thing. Width and thickness do not much matter, so narrow strips of thin metal foil can be used. During the war in Europe, millions of pounds of this material were thrown out into the air from our bombers to mislead the radar on pursuing fighters or the radar used on the ground for directing anti-aircraft guns.

Still another way of avoiding the seeing eye of radar is by making the surface a poor reflector for the waves in the radar pulses. Have you ever seen a sample of "non-reflecting" glass? The glass is coated with a material of just the right thickness and just the right optical density (Page 158) so that the waves of light reflected from the front of this layer interfere destructively with the waves reflected from the back, and the net reflection is very small. If you recall the discussion of interference, back in Chapter Seven (Page 148), you may see how this is possible; if you have used a camera or a pair of binoculars with lenses treated to make them non-reflecting you know, of course, that it can be done.

In the same way, a metal surface can be made a poor reflector for short radio waves by coating it over with a layer of the right material, in the right thickness. The thickness needed is a certain fraction of a wave length—an inch or so, if the purpose is to hide from a 10-centimeter radar set. Such non-reflecting layers are much too thick for use on aeroplanes, but they were tried to some extent on enemy submarines in the latter part of the war.

V. *What Good Is Radar in Peacetime?*

Do you remember the announcement, back in January of 1946, that Army radar experts had sent a signal to the moon and received an echo back? If you have forgotten how long the round trip took you can easily figure it out, using the equation on Page 292 and remembering that the moon is 240,000 miles away (the answer is 2.6 seconds). This first bit of radar exploration into outer space required a very strong transmitter, a specially-designed directional antenna, and a very sensitive receiver. The wave length used was a little less than three meters. In tuning the receiver, allowance had

to be made for the Doppler Effect (Page 260) due to the motion of the moon toward the earth; the speed of approach was 682 miles an hour at the time the experiment was made.

Signalling to the moon is certainly one peacetime use for radar. However, it hardly seems likely to become a large-scale business. We can safely discount most of the glowing speculations the newspaper editors allowed themselves to make when the news first came out. You know enough about radar by now to recognize, for example, that it is still far too blunt a probe for examining the surface detail of the moon or the distant planets. In fact, the beam used in the Army experiment was so broad that most of its energy went right on past the moon.

In going to the moon and returning, a radar pulse has to pass through the ionized layers of the upper atmosphere, and it may be that some useful information about these layers can be learned by sending radar pulses through them. For this purpose, the radar experts would gladly trade the moon in for a moderate-sized reflector located a thousand miles or so above the earth. The moon would be used as a mirror for the waves only because nothing more convenient is available out there.

But what of the more mundane uses for postwar radar? The task of converting radar to serve in the ways of peace is still in its early stages, and it would be guesswork to say how far it will go, or how quickly. Still, without making any definite predictions, we can have a look at some of the possibilities.

Ground radar stations, set up at airports, are already being used to locate aircraft approaching in fog or storm and to "talk the pilot down" to a safe blind landing on the runway.

The airborne sets that were used for navigation and blind bombing have obvious applications to postwar air travel. As airliners become larger and the apparatus becomes lighter and simpler, they may come into common use as safety devices, helping the pilot to keep on his set course and away from mountainsides. Already, radar sets are being used on ships to aid navigation at night and in fog or storm.

Another wartime aid to navigation—not exactly radar, but a sort of cousin to radar—seems likely to be widely used. This is "Loran." Loran employs radio pulses of long wave length which, you recall, will follow the curvature of the earth for great distances. The working range of a Loran station is so great that whole oceans and whole continents can be spanned by systems of stations located on the coasts.

A single Loran system consists of four stations, in two pairs. One station of a pair is called the "master," while the other is a "slave." The two master stations are located together, with one slave on each side of this location and many miles away. Each master station sends out, at regular intervals, a pulse which spreads in all directions about it. This pulse, reaching the slave station, triggers it to send out a similar pulse. In all, then, a set of four pulses goes out, one from each station.

The pilot who wants to use the Loran system has to have in his aeroplane a receiver that will respond to the pulses and measure how long the pulse from each slave station is delayed behind the pulse from its master. With this information, he can consult a chart and fix his location within a mile or so. If you have ever flown above the ocean or above a dense sea of clouds, you will recall that landmarks are conspicuous for their absence, and you can understand that such definite and reliable information as to where he is might often be most comforting to the pilot. Loran can be used by ships at sea as well as by aircraft in the air. Several ships are already equipped with the receivers.

Perhaps the knowledge and techniques of radar, rather than the radar devices themselves, will prove to be the most important gleanings from this wartime field. The radar work has opened up for our use a new region in the spectrum of electromagnetic waves. Before the war, we thought of frequency-modulation radio and television as short-wave developments. But radar, moving ahead to 50 centimeters, then to 10 centimeters, and then to 3 centimeters, has left these prewar marvels far behind. Already there is talk of television systems operating in the band of radar wave lengths, bringing us pictures in full colors with frequency-modulation voice radio tucked into the gaps between the television signals. It is not impossible. We must wait and see how long it takes.

The telephone and telegraph engineers, too, are looking forward to using short-wave beams for carrying messages and speech from one city to another. Maybe the poles and wires that now march across the country beside the railroads and the highways will soon be gone, replaced by a network of microwave relay stations on hilltops miles apart.

VI. *How Are Things Heated by High Frequency?*

Have you ever been a customer for one of those new automatic hot dog dispensers, where the frankfurter in its roll and neatly

wrapped in waxed paper drops down into a little slot and is heated up to a sizzling temperature before your very eyes? Or have you ever seen the demonstration in which popcorn is popped in a glass jar between two blocks of ice, and gone up front afterwards to sample the product? Or has your doctor ever held the coil of a diathermy machine up near your stiff and aching shoulder until you could feel a pleasant warmth and a relief of the stiffness? If so, you have had personal contact with high-frequency heating.

Before leaving the subject of radar and television and such things, we might look briefly at this rapidly growing application for oscillating circuits.

Compared with the frequencies of radar sets (a 3-centimeter radar operates, as you can see by using the formula on Page 272, at 10 million kilocycles) the frequencies used for heating are not high at all. For some purposes a frequency of only one kilocycle is used; many industrial heaters, as well as the diathermy machines, work at 500 kilocycles; and a mere 80,000 kilocycles is used to warm the hot dog up to edible temperature. But who knows what the future will bring? Radar equipment and knowledge, remember, are only beginning to be available for industrial use. We may yet see radar generators used for cooking hams, or for turning gallons of sticky liquid into grosses of shiny plastic doorknobs.

There are two methods of heating with high frequency. Which one is used depends on what has to be heated. If the object is a fairly good conductor of electricity, like a metal or like the salty juices in a hot dog or in the human shoulder, *induction* heating is used. If it is a poor conductor, as most plastic materials are, *dielectric* heating is used.

In induction heating the object is put into a coil of wire and the oscillating current flows to and fro in this coil. If you recall the discussion of transformers, back on Page 127, you can probably complete the story for yourself: the oscillating current causes an oscillating magnetic field through the coil; as this field changes in intensity the electrons in the metal (or the ions in the salt solution, if the object is such a thing as a frankfurter or a shoulder) are forced to move around in circular paths, first one way and then the other; these moving charges are an electric current; this current, to and fro through the resistive object, heats the object up. You may recognize that the whole system is just a transformer, with the coil as the primary winding and the object as a sort of secondary winding with its

two ends tied together. In an ordinary transformer, if the secondary is shorted while alternating current flows through the primary winding, the secondary quickly gets hot. This very same action, which is carefully avoided in the case of an ordinary transformer, is used intentionally in the induction method of heating.

Have you ever noticed that the iron core of a transformer is usually made, not of solid iron, but of thin sheets or laminations? The sheets are insulated from one another, so that current cannot pass from one to the next. This construction is necessary, to keep the core from becoming overheated by the induction currents that would flow freely around in it if the core were one solid conductor. Aside from the inconveniences a hot core would cause, the efficiency of the transformer would be lowered if energy were wasted to heat up the core.

Dielectric heating makes use of a property of insulators we have not mentioned before, their *polarizability*. These substances, as you know from the discussion on Page 87, are poor conductors of electricity because they contain few electrons or ions that can move freely along when an electric field is applied. But the interior of a non-conductor, or dielectric, is a scene of great activity when an electric field is first applied. All the negative components of the material *start* moving one way in the field, and all the positive components start moving in the opposite direction. If the electric field, once applied, stays constant, these positive and negative parts quickly pull as far apart as the attractive forces between them will allow, and then stop. The material settles down in a new condition, a strained condition, and is said to be "polarized."

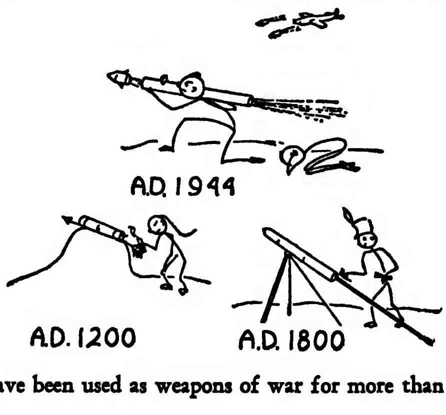
But now suppose the field is reversed in direction. The positive and negative charges then quickly move back past their neutral positions and settle down again, leaving the material polarized in the opposite direction. If the field is reversed regularly and often—in other words, if it is a high-frequency alternating electric field—this to-and-fro motion of the bound charges in the dielectric goes on all the time, one cycle after another. There is some resistance to the to-and-fro motion: you can think of it, if you like, as a rubbing of the parts together when they move past one another. This means that a little heat is generated in each cycle throughout the volume of the material. If there are enough cycles per second (that is, if the frequency is high enough) this heating effect can be enough to raise the temperature of the material rapidly.

Dielectric heating has found its chief application, up to the present, in the plastics industry. There it is used for such purposes as gluing plywood together (a *thermo-setting resin,* which can be applied as a cold liquid and will set up hard and tough when it is heated, is used as the glue) and for "stitching" plastic parts together.

From what has been said about how dielectric heating is done, you might expect that the dielectric object to be heated would be placed between the condenser plates in an oscillating circuit, where there is an alternating electric field. This is the case. But if the object being heated is surrounded by a coil of wire or tubing, you can be fairly sure that the heating is by the induction method, using the alternating magnetic field in the coil.

VII. *Why Are Rockets Useful Weapons?*

Do you think of military rockets—those terrifying things that take off with a whoosh and a roar and a blast of flame from the rear end, and go streaking along through the air toward the enemy—as a very modern invention? Then you may be surprised to learn that rockets have been used in warfare for at least 700 years, ever since gunpowder was first devised. Their history goes back so far that no



Rockets have been used as weapons of war for more than 700 years.

one is sure just when the first rocket was launched with malice. That line in the "Star-Spangled Banner" about "the rockets' red glare" was no flight of Mr. Key's imagination. When he wrote it, back in the War of 1812, the British were actually bombarding the defenses of Baltimore with rockets, rockets that worked on exactly the same principle as those so widely used in the last war, and were not much different in construction.

A rocket, as you recall from the discussion on Page 29, is a *reaction motor,* propelling itself along by throwing material—the hot gases of the rapidly-burning propellant charge—out the rear while the rocket recoils in the forward direction. We can look on the rocket motion in several different ways: as an example of the conservation of momentum (Page 28), or as an example of Newton's Third Law of Motion (Page 10), or as an example of a very simple form of heat engine (Page 200) in action.

The air through which the rocket moves is neither necessary nor useful for the motion. The air merely gets in the way of the rocket in front and gets in the way of the escaping gases behind, and so tends to slow the rocket down. Rockets are at their best where there is no air to hinder them. In fact, the only practicable way that has ever been imagined for travelling beyond the earth's atmosphere is by using a rocket motor.

Most military rockets, from the earliest ones down to the modern bazooka missile, burn a solid fuel, such as gunpowder or one of the newer propellant explosives. This fuel must be shaped so that it will burn rapidly and evenly; a nozzle must be provided to concentrate the blast of hot gases straight backward; and fins to stabilize the rocket in its flight are desirable. Most of the modern improvements in military rockets have been made in such matters of design. Incidentally, the rocket proper is usually only a conveyance for carrying something from one place to another. In warfare, the military damage at the landing-point is done by an ordinary high-explosive shell (or some other kind of military "pay-load") which is pushed along by the rocket motor fastened behind it.

As you can imagine, a rocket is rather more erratic in its flight than is a rotating shell shot from a rifled gun (Page 50). Rockets, in their present state of development, are therefore not of much use where a shell has to be placed precisely on a small target at considerable range. But at close range, or wherever a large quantity of high explosive needs to be placed quickly in a large area without any great precision (as when a beach is bombarded in preparation for a landing) the military rocket is a very useful weapon indeed.

Its great advantage is that it needs no heavy and expensive gun mechanism to take up the recoil. The recoil is taken up by the escaping gases, and finally delivered to the surrounding air. All that is needed is a simple thin-walled tube of sheet metal or plastic, or some sort of light rails, to get the rocket started off in the right direc-

tion—plus, of course, some place for the operator to get where he will not be singed by the hot blast.

The foot-soldier firing his bazooka at an enemy tank would be flattened by the recoil if he had to absorb it in his shoulder. As it is, the hot gas roars out one end of the bazooka and the projectile rushes out the other end; the soldier, if he bothers to notice it in the excitement, feels only a little lessening of the weight on his shoulder after the rocket has left the tube. Similarly, an aeroplane firing a salvo of rockets from tubes or rails under its wing would be shaken and stalled by the recoil, if the recoil had to be absorbed by the aircraft itself. As it is, the pilot may even be in doubt whether the rockets have fired, until he sees them streaking out ahead of him.

The problem of getting heavily-loaded aircraft into the air from a short runway, such as the deck of a carrier, was a serious one during the war. What is needed is a powerful light-weight auxiliary engine that will help accelerate the plane from rest up to its take-off speed in a brief space and time. Once it is airborne, the aircraft can stagger along on the power furnished by its normal engines and can gain altitude, even though slowly.

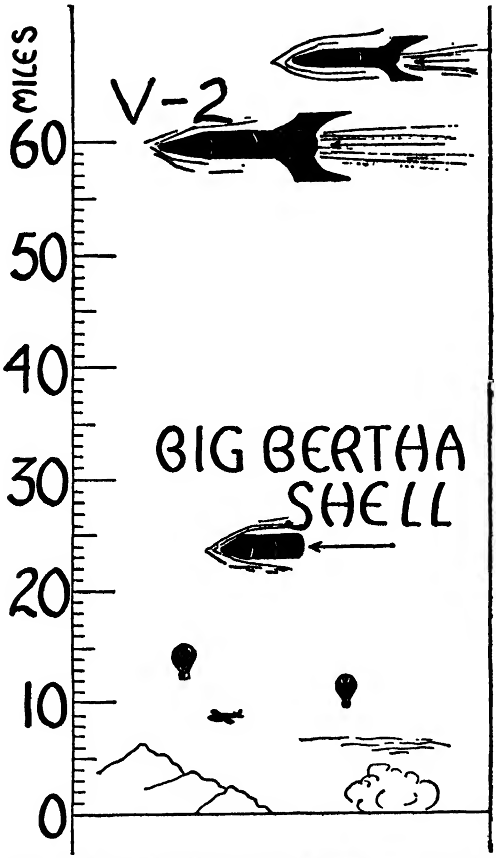
Solid-fuel rocket motors, attached under the wings and throwing the hot gases out to the rear, were used by the Navy to solve this problem. After the rocket motor has spent its charge to blast the aircraft into the air, it is simply a light, hollow metal shell, cheap enough to be jettisoned if it offers too much air resistance. Rocket motors used in this general way are called "thrustors," and these particular units are called "jatos," jato being an abbreviation for "jet-assisted takeoff."

VIII. *How Does a "V-2" Work?*

In size, it is a long stride from the modest bazooka missile to the mammoth V-2, the second of the Nazi "Vengenance" weapons shot against England. These monsters were more than 40 feet long, were five feet in diameter, and weighed more than 12 tons when they started flight. Their nozzles were more than two feet in diameter. They rose, as you may recall, 65 to 70 miles high, far into the stratosphere. Coming down, they travelled through the air nearly four times as fast as sound travels, and buried the explosive "warhead" deep into the earth.

For all its size and range and speed, though, the V-2 works in exactly the same way as its little brother the bazooka missile. Both

are simple rocket motors, pushing explosive shells through space. Both are shoved along by the recoil from hot gases rushing out of a nozzle in the rear. Both are hindered, not helped, by the air around them.



The V-2 went much higher than any previous man-made thing. For details of the lower part of this drawing, see Page 70.

There is a difference in the type of propellant charge. Liquid fuel combinations, such as alcohol and liquid oxygen or gasoline and pure hydrogen peroxide, contain much more available energy per pound than the solid propellants used in military rockets. Whenever the rocket is large enough to carry the pipes and pumps and other accessory equipment required for liquid fuel, such liquid com-

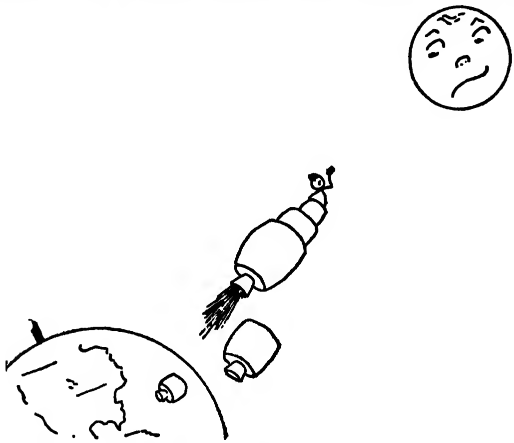
binations are preferable to solid propellants. There is another reason, too, for preferring them: all the burning is done in a small well-designed combustion chamber right back at the nozzle, and this chamber keeps its size and shape unchanged as the fuel is used up. In a solid-fuel rocket the combustion chamber, formed by the walls and the unburned charge, grows and distorts as the charge burns away, thus making the overall efficiency of the motor less than it might be. Actually, the V-2 burned a mixture of alcohol and liquid oxygen.

Are you wondering why the walls of the combustion chamber are not melted down by the fierce flame raging in the chamber? In the early days of experimenting with liquid-fuel rockets much effort was spent, without much success, in trying to find materials that would stand the effects of the inferno. One solution is to make the walls of thin metal, and circulate the incoming fuel over the outside of the chamber before it goes in to be burned with the oxygen. This simple scheme serves two purposes: the flowing liquid helps keep the thin walls safely cool, even on the inside; and the heat that escapes through the walls preheats the fuel so that it yield a hotter flame when it enters the chamber. This "regenerative" design, as it is called, was used on the combustion chamber of the V-2, supplemented by other cooling arrangements.

The bazooka charge burns itself nearly out while the rocket is still travelling down the tube, so that most of the flight is merely a coasting after the initial push. Just so with the V-2: the nine tons of fuel and oxygen are all burned up in about the first minute of flight, in the first 20 miles of the path. The thrust during this period, amounting to some 25 tons, brings the rocket up to a speed of about a mile per second. Thereafter the warhead, with the empty tanks and the idle pumps and the cooling combustion chamber behind it, goes on up and then comes down again, just like a baseball thrown into the air. The whole time of flight, from the flash and roar when the mixture is ignited, to the thud and blast when the rocket plunges to earth again 200 or more miles away, is about five minutes.

The Germans never solved the problem of guiding the V-2 to a particular target. After the missile had left the ground it was on its own. As you might expect, its accuracy was less than perfect. If it had been controlled in flight, perhaps by some radio technique, or by a homing device, it would certainly have been a much more effective weapon.

Are you still interested in that rocket trip to the moon and the planets? You can start out, if you like. The engineers will design for you a multi-step rocket, a succession of rockets all attached together, each one much smaller than the one before it, with the smallest one just big enough to carry you as the pay-load. You will start by firing the largest rocket, then you will drop off its empty carcass and fire the next-largest, and so on. The engineers will not guarantee that it will take you clear outside the earth's attractive field, but some of them will talk optimistically about it. The whole



A step-rocket will probably be needed for flight to the moon and the planets.

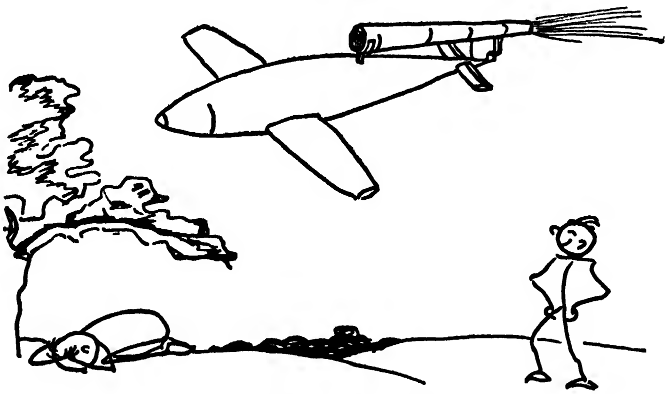
thing may weigh, when you climb aboard, some tens of thousands of tons. You must be prepared to pay well for the ticket. Were you thinking of coming back? That calls for some more steps, all much bigger than the biggest in the one-way rocket. Maybe you'd better decide to visit Grand Canyon instead.

Though interplanetary travel is hardly just around the corner, there are some peacetime uses for rockets nearer home. Thurstors, such as the jato, have many obvious applications. For another example, rockets can carry measuring instruments miles above the clouds and bring back (or send back by radio) much valuable information about conditions high in the stratosphere. It may be that rocket-soundings will someday be used in weather forecasting, as balloon-soundings are now used. You know, of course, that rocket research and development have gone ahead actively since the war ended.

IX. *What Drives a Buzz-Bomb Along?*

The V-1, or "buzz-bomb," the first of the German "Vengeance" weapons, turned out to be a fairly effective tool of warfare, as you recall if you read Mr. Churchill's report in 1944 after the battle against these aerial torpedoes had been nearly won. They did widespread damage in London, and the defense against them tied up much allied effort that could otherwise have been used for attack.

Zipping along at an altitude of a few thousand feet, a little too fast for an ordinary fighter plane to overtake comfortably, shooting a stream of red flame out the back and making a steady buzzing noise like an outboard motor in the distance, the V-1 was an interesting sight to see in the sky over England. The thought that at any



A buzz-bomb (V-1) in flight.

moment the flame and noise might stop and the bomb plummet or glide to the ground to explode its ton of TNT was disquieting, of course—more than one observer has remarked that the buzz-bomb in flight looks most attractive from the rear.

Whatever the aesthetic opinion, the engineers who could bring themselves to consider the matter without bias had to admire the V-1 as a most ingenious device.

The most interesting part of the V-1 is the engine, that length of tubing aft and above the fuselage. It looks like a piece of stovepipe expanded a little at the front end and covered over at that end with a metal sheet full of holes, the back end being left open. Actually, that is about all there is to it. It is the simplicity of the engine that makes it so interesting.

We can be satisfied with a bare list of what is in the fuselage and the wings. At the very front, of course, is the deadly charge of high explosive, with the necessary fuzes. The main body of the fuselage contains a tank of gasoline, a gyro-control (Page 50) to keep the bomb on its course by controlling the rudder and the elevators, a clockwork for shutting off the engine after the bomb has been in the air long enough to get over its target, and perhaps a little radio transmitter to send back a signal which will tell where the bomb is at any instant. There are also two big round bottles of compressed air, one to drive the gyro and other accessories, the other to force gasoline from the tank up to the stovepipe engine.

Now, how does the engine work? In the first place, it is a reaction motor, like the rocket motors we have just been discussing. The stovepipe goes forward rapidly because a jet of hot gas rushes out the back end of it. But, unlike the rocket, the buzz-bomb engine carries along only one of the two things it has to have for its fire—the gasoline. It depends on getting the other component, the oxygen, from ordinary air streaming in through the holes in the front end of the stovepipe as the engine speeds along. For this reason, a buzz-bomb engine, unlike a rocket, will not run except in air.

Each of the holes in the front of the engine is provided with a little flap-valve, opening inward against a weak spring. As the engine moves forward rapidly through the air, these flap-valves push open and let air into the pipe. At the same time, gasoline is squirted in from the tank and rapidly vaporizes, forming an explosive mixture like the mixture in the cylinder of your automobile engine. When this mixture is ignited it burns furiously, building up a pressure in the pipe which closes the flap-valves in the front. The hot gases then blow out the back end of the pipe, shoving the engine forward as they leave. When the mixture is all burned up, the pressure inside the pipe drops (in fact, a partial vacuum occurs in the wake of the explosion) and the flap-valves automatically open again to admit another batch of air.

Once the thing is running along, the successive charges of gasoline vapor and air do not need to be fired by a spark plug, because enough hot gas is left in the tube after each explosion to ignite the next batch of mixture. The gasoline is fed in continuously, the air rushes in through the valves every time they open, and as soon as enough air has been packed in for another explosion, the explosion happens. So it goes, put-put-put, about 40 times a second—until

the gasoline is all used up or until the clockwork turns a valve to shut off the flow of gasoline. Then, watch out below!

All well and good, you may be thinking, but how does it ever get started in the first place? The answer is that it cannot start off by itself. It has to be pushed along until it is going about 250 miles an hour; the flap-valves then open themselves, the gasoline can be turned on, and the first explosion can be fired by a spark plug. After that, it takes care of itself. To get the heavy bomb going as fast as 250 miles an hour requires a powerful push for a considerable distance. The pusher may be a compressed-air plunger, or it may be a rocket-thrustor. In any case, a long launching ramp is necessary.

There is another way, though, for getting the V-1 up to speed and even up to altitude before it is launched. It can be carried aloft on a conventional aeroplane and set free when this airborne platform is flying at high speed toward the target miles away. Once the buzz-bomb is free the launching aircraft can turn around and go home. V-1s started off from such "piggy-back" planes flying over the North Sea continued to fall on England after the original launching areas in France had been overrun by the invasion.

X. *What Is Jet Propulsion?*

Broadly speaking, any reaction motor, whether it be a bazooka missile or a V-2 or the stovepipe engine on a buzz-bomb, is a jet-propulsion engine. If the engine moves forward because a jet of hot gases is rushing out of a nozzle in the rear, it is a jet engine, or a reaction motor, whichever you choose to call it. Here, however, we will be thinking particularly of jet engines to be used for propelling piloted aircraft with wings.

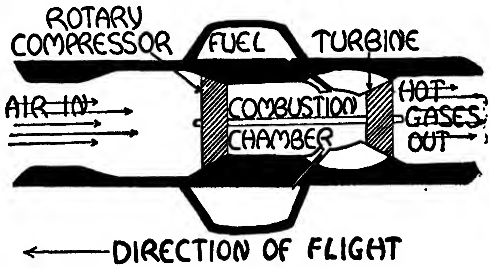
Actually, we cannot profitably do more than look just briefly at some of the general principles of such engines. The developments in jet-propelled aircraft are coming along so fast that any detailed descriptions written now would be out of date before this book can be printed.

Since the aircraft is to have wings and be supported by the air, a supply of oxygen will always be available around the engine. This means that the engine can be designed to burn air and gasoline (or fuel oil) together, as the buzz-bomb engine does. The aeroplane does not need to carry both the ingredients of combustion along with it, as a rocket does. Moreover, the oxygen is not the only component of the incoming air that is useful for the jet propulsion. The nitro-

gen, too, is used. It enters as a stream of slow-moving cold molecules, is heated in passing through the combustion chamber, and is then thrown off as a fast jet of hot molecules, adding its part to the forward thrust of the combustion gases. In fact, a jet engine is usually designed to take air aboard much faster than it needs air for combustion. We might say that it propels itself largely by taking cold air in the front and throwing hot air out the rear, the air being heated by combustion of the fuel.

To make a powerful engine, obviously, we have to cram air and liquid fuel into the combustion chamber very rapidly and burn them there. There is no trouble about feeding in the fuel as fast as we please, but to supply the air at the required rate is another problem, especially at high altitudes where the air is thin.

You may remember that we met this same problem back on Page 203, when we were talking about the difficulty of operating con-



A turbo-jet reaction motor, such as is used in some propellorless aircraft.

ventional aircraft engines at high altitude where the air pressure is low. There, a compressor called a "supercharger" is used to pack enough explosive mixture into the cylinders in each cycle. Sometimes the supercharger is driven by the rotating crankshaft through gears; sometimes it is driven by a turbine that is placed in the exhaust pipe and is connected to the compressor by a simple shaft. This practice suggests an answer to our problem with the jet engines: it can have a compressor to draw in the air and pack it into the combustion chamber. Since the jet engine is not going to have any crankshaft, we shall have to make the air-compressor a turbine-driven affair, placing the turbine back of the combustion chamber where the hot gases will spin it around as they rush through it on their way out to the jet.

The engine, according to this design, is a long tube containing,

in order from front to back, the compressor, the combustion chamber with fuel pipes feeding into its sides and a continuous fire raging within it, the turbine to drive the compressor by means of a rod running back through the combustion chamber, and finally the jet itself, where the flame and the heated air roar out. Admittedly, it is a crude design. But it does contain the essentials of the present-day jet engine—the next propellorless aircraft you see overhead or at an airport will, most likely, have an engine that fits this general description.

Perhaps, though, the engine will be even simpler. It may not have the compressor-turbine combination. By proper design of the air intakes, it is possible to scoop up air fast enough in flight to supply the demands of a powerful engine, so that no moving mechanical parts are needed. Engines of this type are now being developed.

Before we leave the subject of rockets and jets, a word about their efficiency is in order. The efficiency of any reaction motor, you may be surprised to learn, increases rapidly as the motor goes forward faster and faster. The efficiency reaches its peak value when the forward speed of the rocket or jet engine is just equal to the speed of the jet back out of the nozzle—that is, when the nozzle simply leaves a stationary cylinder of hot gas behind it. This speed, for present-day motors and fuels lies somewhere between 800 and 11,000 miles per hour, depending on the fuel and on the design of the motor.

The motor can, of course, go faster than this most efficient speed, though it wastes energy by doing so. No matter how fast the motor is going forward, it can always give itself an additional forward push by discarding material to the rear. It can continue to gain speed, even when the gases it ejects actually trail along behind it, moving forward (with respect to the earth) like the motor itself, instead of backward. As a matter of fact, however, the reaction motors of today almost never reach the speed of most efficient travel. The V-2 at the end of its burning period came close to its most efficient speed. But the V-2 started from rest, so that most of its fuel was used while its speed was still low and its efficiency correspondingly low. It has been computed that the V-2 actually wasted more than 99 per cent of the energy stored up in its fuel and oxygen.

Since it has no moving mechanical parts (or few, at most) to waste energy by friction, a reaction motor travelling at its best speed can be the most efficient of all heat engines, much better than a steam turbine or the reciprocating engine in your automobile. On the

other hand, there are still many problems to be solved before the theoretical efficiencies can be attained in practice. And even in theory, the efficiency is deplorably low at low speeds. There is no use replacing your automobile engine with a reaction motor if you intend to be a law-abiding citizen and keep below 50 miles an hour.

XI. *How Do Helicopters Differ from Aeroplanes?*

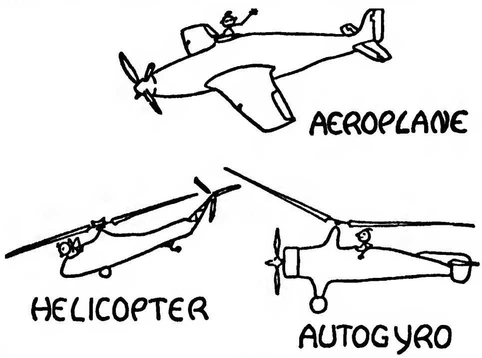
Have you ever wished, as you sat impatiently in your car in the midst of a traffic jam, that you could rise right up out of it all and make your way to your own back yard as the crow flies? Perhaps you can, some day. An airborne substitute for the personal automobile would have many advantages. Compared with one-dimensional roads, the air with its three dimensions offers almost unlimited freedom for travel. Moreover, the streets up there never need repair, and snow does not pile up on them.

If you ever do take to flying down to work in the morning and back home at night, it will probably be in some sort of helicopter. These "flying windmills," which can go straight up and down and can even stand still in the air as long as you please, came in for a rapid development during the war. They fully proved their reliability and usefulness for many purposes. We must wait and see how quickly they will come into common use for commercial and private flying. One of the leaders in helicopter development predicts that they can be built to sell for no more than a medium-priced automobile, if the volume of production is high enough. Will you need six arms and the agility of a ballet dancer to fly your own helicopter? Of course not!—but the present-day models will have to be greatly simplified as to control before a beginner can trust himself to handle one of them.

So much for the future. Looking backward, we have to look a long way to see the beginning of the thought that man can lift himself up into the air by means of a helix or airscrew. More than 400 years ago Leonardo da Vinci drew up sketches for an aircraft to be lifted by turning a helix about a vertical axis. His design was impracticable, but he had the right idea. All along, research on this method of conquering the air has run parallel with the work on conventional winged aircraft. In 1907, only four years after the Wright Brothers made their successful flights at Kittyhawk, Louis Breguet in France climbed aboard the helicopter he had built, speeded up the engine, and felt the four revolving windmills overhead lift the

contraption off the ground. But there were many hard problems to master, and until the past few years no one felt very certain about the future of the helicopter. Now, apparently, it is here to stay.

Just what is it that keeps a helicopter up? If you understand how an aeroplane stays aloft, you can easily answer the question about the helicopter. In both cases, of course, the machine is supported, essentially, by the air underneath. As the aeroplane wing moves forward through the air, the air flows faster over the top of the wing surface than under the bottom—the wing is designed so this will be true. According to Bernoulli's Principle (Page 77), the pressure of the air above the wing is therefore less than the pressure under the wing; the unbalanced upward pressure on the wing is what holds the



Bernoulli's Principle explains how these three craft stay up in the air.

aeroplane up, opposing the downward pull of the earth. The propellor blades are designed like little wings, and they have the same function: as they are turned through the air by the engine each blade sets the air to whirling about it, fast in front and slower behind. Again, Bernoulli's Principle says that the pressure will be higher on the back side of the blade than in front. It is this unbalanced forward pressure on the blades that pushes the aircraft along, just as the unbalanced pressure under the wings pushes it up.

As for the helicopter's windmill blades, they too are shaped and pitched so that as the engine turns them around through the air a net upward pressure on each blade results. The force from this pressure lifts the helicopter into the air.

If the helicopter pilot wants to go forward or backward or sidewise, he can do it in several ways. Most simply, he can tilt the shaft of the windmill a little away from the vertical, in the direction he

wants to go. Or he can get the same result, if he has a little auxiliary propellor out at the tail of the helicopter, by using this propellor to tip the whole craft slightly toward the intended course. Still another method is by wiggling each blade about its own length as it goes around and around. Perhaps this last method does not sound very effective to you, but it is a fact that if the machinery for making this cyclic change of pitch (as it is called) is properly designed the pilot can make the helicopter scuttle about in any direction he pleases. Each helicopter designer has his own ideas as to which of these methods of control is the best.

Have you been recalling Newton's Third Law of Motion (Page 10) and wondering why the windmill does not stand still and let the engine spin the cabin and the pilot around? It certainly would —rather, both would spin in opposite directions, with the windmill turning slower than the cabin—if something were not done to prevent it. In a single-airscrew helicopter, a little auxiliary propellor out at the end of a long tail is commonly used to give the opposing torque that keeps the fuselage from turning. If two airscrews are used, rotating in opposite directions, their torques tend to cancel, and the problem of keeping the nose of the craft pointing in a fixed direction is then simpler.

That odd-looking craft you saw a few years ago, flying over the city with a long banner behind it exhorting you to "Try Thistlethwaite's Toffee" or "Drink Blurp! It Won't Kill You Instantly" was probably an *autogyro* and not a helicopter. The two look alike, but the autogyro is actually closer kin to an aeroplane than to a helicopter. Like the aeroplane, it has a propellor out in front to pull it forward through the air. The windmill blades overhead are not driven around by the engine, any more than the wings of an aeroplane are flapped up and down by the engine. They turn only because the autogyro is moving forward through the air—the blade shape is designed to make them turn. Because they turn, they move through the air faster than the autogyro moves forward, and thus they give more lift than if they were attached rigidly to the craft. It is this combination of high lift with low forward speed that enables the autogyro to take off at a steep angle (actually, the windmill is connected to the engine before take-off and is brought up to speed, then it is left to "free-wheel" and the engine is connected to drive the propellor). But an autogyro cannot move straight up, nor can it hover in the air. When the forward motion stops, like an aero-

plane it must come down. The recent developments in helicopters seem likely to make the autogyro obsolete. For the past several years it has not been prominent in the news.

If the engine of an aeroplane fails, the pilot has to look around for an open space and hope he can glide to a safe landing. In a helicopter or autogyro a forced landing is a fairly leisurely affair. The windmill, left, to itself, turns around as the craft falls and so breaks the descent—rather like a maple seed swirling slowly downward from the branch to the ground. If the windmill comes off you are left up there, of course, with nothing to hold onto—a temporary predicament, but unpleasant nevertheless.

CHAPTER FOURTEEN

ATOMIC ENERGY IN WAR AND PEACE

I. *What Is This Chapter About?*

One question this Chapter will *not* answer is the tremendous question: how shall mankind free itself from fear of atomic bombs? You are vitally interested in this problem, of course, as is everyone else. But do not look here for any contribution to its solution.

How potent a weapon is the atomic bomb? That is another question we shall not try to answer. The military effectiveness of any explosive depends on many factors. Even the experts would hesitate to say, when so few atomic explosions have been studied, just how many tons of TNT one ton of atomic bomb is worth.

Are you especially interested in the history of the atomic bomb project—how many people worked on it, who they were, and where and how the job was done? It is a fascinating and exciting story, well told in the Smyth Report,* the official account that was released by the War Department soon after the two bombs were dropped on Japan in August of 1945. But it is a fairly complicated story, and we are not going to review it here in its historical order.

Instead, we are going to consider in this Chapter a few of the scientific principles that are involved in the "harnessing of the atom." You know, of course, that the startling results in science are almost never reached in a single step. Rather, almost every one is the outcome of patient work, careful observation, and much trial and error. The atomic bomb is no exception to this rule. Back of it lies 50 years of study. First, let us look at some of the information accumulated in those 50 years. Then we can understand what happens when an atomic bomb explodes, and we can look ahead to some of the peacetime uses of atomic power.

II. *What Is in the Nucleus of an Atom?*

An atom, as you recall from Page 58, is practically all empty space. Suppose we take, in imagination, a trip from the outside of

* *Atomic Energy for Military Purposes*, by Henry DeWolf Smyth (Princeton University Press, 1945).

an atom right down to its center. All the way we shall be kept busy dodging the electrons as they whirl past us in their orbits. Pausing to examine the electrons, we find they are all alike, that each one is charged negatively, and that the mass or weight of any one of them is very small in comparison with the mass of the whole atom. If we count up these whirling electrons as we go along, we find that the total number of them depends on the kind of atom we are exploring. If it is a hydrogen atom there will be only one electron. If it is a copper atom there will be 29. If it is an atom of uranium, which has more electrons per atom than any other element in nature, the number will be 92. Still, taking them all together, the electrons will account for only a few ten-thousandths of the total mass of the atom.

Where, we might wonder, is the remaining mass of the atom—most of it, in fact—hidden? We might wonder why, with so many bits of negative electricity whirling around within it, the atom seemed to be quite uncharged before we started down into it. We might wonder, too, why the electrons continue to whirl around in such close quarters. Undoubtedly they all repel one another. Why, then, do they not all fly apart? What holds the atom together?

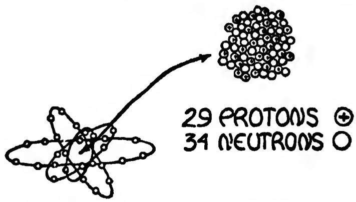
Down at the very center of the atom we should find the answer to all these questions. There sits the nucleus, a tiny particle no larger than a single electron, but massive enough to make up almost all the weight of the whole atom. It carries a positive electrical charge, just the same in size as the total negative charge on all the electrons whirling about it. It is the attraction of this positive charge for the negative electrons that holds them in the atom. The atom as a whole is electrically neutral because it contains as much positive electricity (on the nucleus) as negative electricity (on the electrons).

To fix the scale of things in your mind, suppose that the nucleus, when we get to it, is the size of a baseball. Then our trip back out of the atom, from the nucleus to the outermost electron, will be about half a mile long. The actual size is, of course, inconceivably small—a hundred million atoms side by side would fill a length of only about one inch, and if all the nuclei from these hundred million atoms could be put together in a heap they would make a speck too small to be seen.

Perhaps you know already that the so-called atomic bomb is really a nuclear bomb. The bomb, like the other devices for releasing "atomic energy," works by changing nuclei of one kind into nuclei

of another kind. In these nuclear reactions the whirling electrons play only a secondary role. The nuclei of atoms, and not the electrons, will get most of the attention in this Chapter.

What is in a nucleus? Fortunately, the nucleus does not seem to be a very complicated structure. To make up any nucleus, from the simplest to the most complex, you need only *two* kinds of particles, *protons* and *neutrons*. A proton, as you may recall from Page 82,



All copper atoms have 29 electrons whirling in various orbits around a central nucleus, and 29 protons in the nucleus. This copper atom, Cu-63, has 34 neutrons in its nucleus. The other stable copper atom, Cu-65, has 36 neutrons in its nucleus.

is a particle with a positive charge exactly the same size as the negative charge on an electron, but weighing about 1800 times as much as an electron. A neutron is almost equal to a proton in mass, but the neutron has no electrical charge at all. You can think of the protons and neutrons in a nucleus, if you like, as so many apples and pears in a Cellophane bag. Change the number of either one, and you have a different kind of nucleus.

Of course, you may want to ask a lot of embarrassing questions about this simple picture of a nucleus. Are the protons and neutrons stationary, or do they move about somehow in the nucleus? Why do only a few particular combinations of protons and neutrons occur in nature (actually, there are only some 250 different kinds of nuclei in the natural elements)? How can so many positively-charged protons stick together in such a tiny space? What keeps them from flying all apart?

All these questions are indeed embarrassing. In fact, no one knows the answers to them. To find the answers to these very questions is one of the main tasks before Physics today. Fortunately, though, we do not need to know all these things about the nucleus in order to make a nuclear bomb; and we can understand a number of things about nuclear energy and its release without having a fully satisfactory model of the nucleus in mind. For our purposes, the simple picture of a nucleus as a close-packed cluster of protons and neutrons, like apples and pears in a sack, will serve us very well.

III. *What Are Isotopes?*

Shall we go into the business of making up nuclei from their raw materials, the protons and neutrons? No one has ever done it—in practice, the most that can be done is to change one kind of nucleus into another, and even this modest achievement takes some complicated equipment. But we can overlook the practical difficulties and go ahead (in imagination) as if it were all very easy.

We shall need, of course, a supply of protons and a supply of neutrons. If we want to finish off the job by making complete atoms, instead of bare nuclei, we shall also need a supply of electrons. Then, when we have completed a nucleus containing, let us say, 29 protons, we can turn 29 electrons loose in its neighborhood and we shall have a perfectly good atom of copper.

We might suppose, before we started, that we could do just as we please about the proportions of protons and neutrons in the nucleus. If it is a copper nucleus we are constructing, there must be just 29 protons, of course, no more and no less. But is there any reason for not leaving out the neutrons altogether, or any reason for not putting in several hundred neutrons, supposing we feel generous about it?

If we tried various combinations according to whim, we should soon find that Nature has some fairly definite rules about the number of neutrons that ought to be put together with 29 protons to make a nucleus. With 34 neutrons, or with 36, all is well—the nucleus, once made, will last indefinitely. But if we try to use 35 neutrons, our nucleus is unstable. It will last only about 13 hours. If we start out with 33 neutrons, the nucleus will last only about 11 minutes. If we add 37 neutrons to the 29 protons, the resulting nucleus lasts only about five minutes. What happens if the number of neutrons is much more than 37 or much less than33 no one knows—the practical difficulties have prevented people from ever making such nuclei for study. Presumably they are even less stable than those that have been made and studied.

This case of copper illustrates a very general rule about nuclei, which has only one or two trivial exceptions: a stable nucleus—that is, a nucleus which will last indefinitely—has to contain as many neutrons as protons, plus a small surplus of neutrons if there are many protons present.

For some certain numbers of protons, only *one* choice of the number of neutrons is possible. For example, if we choose to have

nine protons in our nucleus (this would be the start of a fluorine atom) it will not be stable unless it contains just 10 neutrons. For another example, 90 protons will make a stable nucleus with just 142 neutrons, no more and no less—this nucleus, containing 232 particles in all, is the nucleus of a thorium atom.

On the other hand, for some choices of the number of protons two or more—sometimes as many as 10 or 12—different numbers of neutrons can be used to make a stable nucleus. Our example of copper is a case of this kind. With 29 protons either 34 or 36 neutrons can be used. In either case, the finished atom will have just 29 electrons whirling about the nucleus. The chemical properties of the atom depend only on how many of these electrons are present; the nucleus, hidden deep away in the cloud of electrons, is not at all concerned in any ordinary chemical changes. So the two kinds of atoms, one with 34 neutrons in the nucleus and one with 36, are just alike chemically. They are both atoms of the chemical element copper.

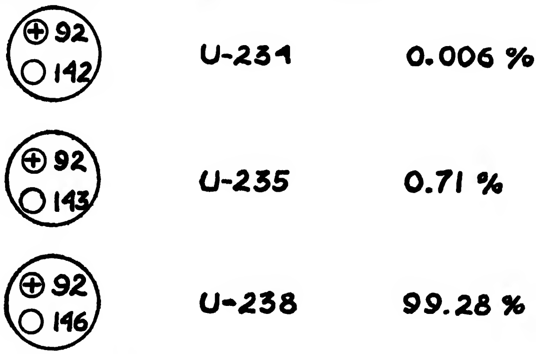
These two kinds of atoms are called the two *isotopes* of copper. Isotopes, to sum it up, are chemical twins of one another, differing only in the mass of the nucleus. Usually the difference in mass is quite small. For copper, one isotope has a total of 63 nuclear particles, while the other has 65. Recalling that the proton and the neutron have almost exactly the same mass, you can see that the mass difference, two units out of 63, is only about three per cent.

In nature, wherever an element with several isotopes occurs, they are always mixed together in certain proportions. For example, the copper in a common penny contains 68 per cent of the lighter atoms, those that have only 34 neutrons in the nucleus, and 32 per cent of the heavier atoms with 36 neutrons in the nucleus. These same proportions are found in copper everywhere, no matter where it is mined.

Uranium, as you know, is a very important element for the making of atomic bombs and the release of atomic energy. We are going to be much interested in the different uranium nuclei. This is as good a time as any to get acquainted with them.

Uranium has three natural isotopes. The lightest of the lot contains 92 protons and 142 neutrons, a total of 234 particles. This isotope is not very abundant in the natural mixture: only one uranium nucleus out of every 17,000 is of this kind. The next heavier isotope contains 143 neutrons with its 92 protons, a total of 235

particles. It is rather more plentiful, but still scarce: only one out of every 140 uranium atoms in nature is of this kind. The heaviest of the three, and by far the most abundant, has 146 neutrons, or a total of 238 nuclear particles. It makes up more than 99 per cent of the natural mixture of uranium isotopes. Finally, we shall need



Uranium has three natural isotopes: left, their nuclear contents; center, their names; right, their relative abundances in nature.

names for the uranium triplets. Following the custom, we can call them U-234, U-235 and U-238. The "U" stands for "uranium," of course, and the numbers, as you will recognize, tell how many nuclear particles, protons plus neutrons, are in each nucleus.

IV. *What Is Heavy Water?*

Do you remember, back in the war, some bombing raids on a plant under Nazi control in Norway which the newspapers said was producing "heavy water?" Perhaps you wondered at the time what kind of queer chemical heavy water might be, and why an enemy factory producing it should get the same unwelcome attention as an aircraft factory or a munitions plant. The answer to the second question will appear a little later. First, let us see how heavy water differs from ordinary water.

If someone gave you a bucketful of heavy water you probably would never guess there was anything extraordinary about it. It would look and taste just like the common variety. You could drink it or wash your hands in it and be none the worse off. But if you had a bad egg, just far enough gone so that it would settle only gently to the bottom of a bucket of ordinary water, this egg would float in the bucket of heavy water. It is this abnormally high density that

gives the substance its name. Chemically, heavy water and ordinary water are quite alike.

As you recall from Page 101, water is a compound of the two gases hydrogen and oxygen. Each molecule of water contains two atoms of hydrogen and one atom of oxygen. We can describe heavy water, very simply, by saying that *heavy hydrogen* atoms are present in each molecule of heavy water, instead of the ordinary hydrogen atoms that are present in the molecules of ordinary water.

But what is a heavy hydrogen atom? How does it differ from an ordinary hydrogen atom? They have the same chemical properties, which means that they have the same number of electrons—just one, in fact—whirling around the nucleus. This means, in turn, that the two nuclei must contain the same number of protons—again, in fact, just one proton. But the number of neutrons, you recall, can sometimes have different values, for a given number of protons. The case of one proton, it turns out, is one of these. The proton can be alone (this is the nucleus of ordinary hydrogen) or it can have one neutron along with it. This double-weight nucleus, with a single electron revolving around it, is an atom of heavy hydrogen. Heavy hydrogen and ordinary hydrogen, in other words, are just a pair of isotopes. We could designate them, following the custom for uranium, as H-1 and H-2, though these names are actually not commonly used.

In nature, two out of every 10,000 hydrogen atoms are of the heavy variety, with a nucleus consisting of one proton and one neutron. Wherever hydrogen occurs, in the atmosphere, in the water of the oceans, in petroleum, and in plants and animals, this proportion between the two isotopes is found.

V. *How Can Isotopes Be Separated?*

You may be wondering *why* anyone ever wants to separate isotopes, anyhow. A wire made of ordinary copper, with Cu-63 and Cu-65 atoms all mixed up together, will conduct electricity just as well as a wire made of pure Cu-63. The coffee tastes just the same, whether heavy water or ordinary water is put into the percolator. Why bother, then?

It is a good question. As a matter of fact, before the work on the atomic bomb project began, no one had any reason for wanting to separate isotopes, except in minute quantities for experimental purposes. All the large-scale applications for atoms concerned only

their chemical properties. That is, the only thing that mattered was the number of electrons in the atom, or the number of protons in the nucleus. No one needed to worry about how many neutrons were present.

But if you are planning to do things with the nuclei of the atoms, then it is a very important question how many neutrons are present. The properties of the nucleus, such as its ability to be changed over into another kind of nucleus, depend critically on how many neutrons it contains. The isotopes of a given element are all alike chemically, but they are all different if it is a nuclear reaction, rather than a chemical reaction, that you are proposing to deal with.

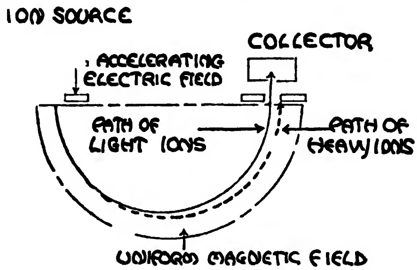
The U-235 nucleus, for example, has certain properties that make it useful for atomic bombs. The U-238 nucleus does not have these properties. In fact, U-238 is worse than inert—it actually has a poisoning effect in an atomic bomb. A bomb cannot be made with the natural mixture of uranium isotopes, for this mixture is practically all U-238. To make an atomic bomb of uranium, the first step is to pick out the few U-235 atoms (one in 140, you recall) and throw away the U-238.

How can it be done? There is no use, of course, in even trying to separate isotopes by purely chemical methods, such as treating the substance with acids or bases. All these procedures will affect only the outermost electrons. The nuclei, deep down in the cloud of electrons, will go along together through all the chemical changes, and the ratio of U-238 to U-235 at the end of the work will still be 140, just as it was at the start. The two atoms differ only in mass; if they are to be separated, the method must make use of this mass difference and nothing else.

Actually, two different methods for picking U-235 atoms out of natural uranium were developed, in the course of the bomb project, to the point of yielding U-235 in sufficient quantities and sufficiently pure. Both methods use the slight difference in mass—only three nuclear particles out of 235, or a little more than one per cent—between U-235 and U-238.

One of these methods, known as "electromagnetic separation," works in the following way. First, the atoms of the mixture are converted to singly-charged ions, by knocking one electron off from each atom (this process of ionization is described on Page 90). The ions are then speeded up by an electric field. Then the stream of ion-mixture enters a magnetic field, where the ions move around on

circular paths. The lighter U-235 ions move on a slightly smaller circle than the heavier U-238 ions. The stream thus breaks up into two circular streams, and when the two are halfway around a circle they are far enough apart so the lighter ions can be collected separately and changed back to uncharged atoms.



U-235 can be separated from U-238 by sending fast uranium ions around semicircular paths in a uniform magnetic field.

The other method, known as "separation by gaseous diffusion," involves no ionization and needs no electric or magnetic fields. It makes use of the fact that the atoms of a gas, moving about at a given temperature (Page 187), have an average speed that depends on their mass. In gaseous uranium the lighter U-235 atoms are moving, on the average, a little faster than their heavier U-238 twins. The difference in speed is very small, even much less than the difference in mass, but with patience and ingenuity it can be used to separate the two kinds of atoms. What is done is this. Some long narrow hallways are provided, and the gas atoms are allowed to run races with one another down these hallways. The U-235 atoms, moving a little faster on the average, have a little advantage over the U-238 atoms in these races. On the average, the U-235 comes out ahead, and can be collected and removed before the pack of U-238 atoms catches up with it. But the U-235 often loses the race, too, so the race must be repeated many times in order to do an acceptably complete job of separation.

You understand, of course, that the hallways are not the size of ordinary halls in a building. Actually, they have to be no larger than about four ten-millionths of an inch in diameter. Such a tiny channel can handle only a minute flow of racing atoms, so there must be myriads of channels all in action at once if any sizable quantity of U-235 is to be separated. Moreover, the collection of the desired

U-235 cannot be done with a pair of tweezers. Pumps, and a complicated system of moving the material from one place to another, have to be used. But these problems can be solved. They have been solved, in fact, and a vast and complicated separator has been built, in which the U-235, after running thousands of races, emerges as the unquestioned winner. The design and construction of this enormous plant was one of the biggest problems in the whole bomb project.

Perhaps you have been wondering if uranium is really a gas at ordinary temperatures. This is probably the place to confess that, for simplicity, the operation of both the electromagnetic and the gaseous diffusion separators has been described a little untruthfully. In both methods, actually, not the uranium atoms, but molecules of certain gaseous compounds of uranium are used. Uranium itself is a heavy metal, rather like tungsten in appearance, which does not even melt until it is nearly white-hot. If the atoms of uranium are to be handled separately at ordinary temperatures it is necessary to surround each atom with atoms of another element to make a compound of free-flying molecules. Uranium hexafluoride, in which each uranium atom is combined with six fluorine atoms to make a molecule, is mentioned in the Smyth Report as a possible gas to use. If you will re-read the descriptions of the two methods, substituting "molecule" for "atom" throughout, you will have a more precise account of what happens. The principles, of course, are exactly the same, whether atoms or the more practicable molecules are used.

Both these methods for separating isotopes were known long before the war began, and had been used on a very small scale for separating experimental samples of various materials. But never before had there been a need for pounds of output instead of submicroscopic quantities. It was no simple task to develop these laboratory methods to the scale of huge factories, and no one was certain at the start that it could ever be done.

Have you ever seen a centrifugal cream separator (Page 47), where the heavier milk drifts to the outside wall of the spinning can, leaving the globules of lighter cream at the center? This same principle of separation by centrifuging can be used to get the heavy atoms of U-238 apart from the lighter U-235. There are several other methods of doing the job, too, but all of them are even more difficult in practice than the two that were adopted for the bomb project.

If anyone ever needs to separate Cu-63 from Cu-65 (or any other pair of isotopes, for that matter) the same methods that succeed for U-235 and U-238 can be used. If the two atoms differ widely in mass, the separation problem is relatively easy. For example, heavy hydrogen can be separated from its half-weight twin, ordinary hydrogen, by fractional distillation and by several other methods that would not work at all effectively if the atoms were much nearer alike in mass.

Have you been wondering about the third member of the uranium family, little brother U-234? The fact is that you may as well forget about him. There are only some 60 U-234 atoms in every million, as you recall, and they do no known harm in an atomic bomb or in any of the other atomic energy applications. In the various separation processes, U-234 tags along close behind U-235 and the two are collected together.

VI. *What Is a Cyclotron?*

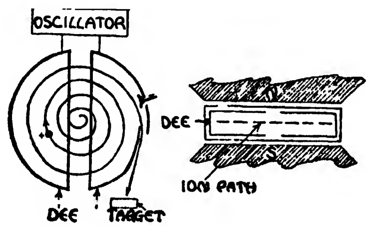
Perhaps you have not even seen the word "cyclotron" since before the war. The cyclotron is a very important instrument for studying nuclei, and all talk about such things was taboo while the atomic bomb was in the making.

To jar a nucleus and change it, perhaps, into another kind of nucleus, you have to hit the nucleus with a bullet of some sort, no larger than the nucleus itself. A single proton, or a heavy-hydrogen nucleus consisting of a proton and a neutron (this nucleus has the special name of "deuteron"), or a helium nucleus containing two protons and two neutrons, can be used as a bullet. All these particles are positively charged, which means that they must be shot toward the target nucleus with great speed if they are to avoid being slowed down by the attractive cloud of electrons and bounced back by the positive charge on the nucleus itself. The cyclotron, in effect, is just a gun for shooting these nuclear bullets with the high muzzle velocity that is required. There are other machines, too, for bringing nuclear bullets up to high speed, but the cyclotron has been the most generally useful and versatile gun in the whole arsenal.

The pictures, if you recall them, show a great solid-looking block of iron and coils, with wires and pipes coming away from it and two or three smallish scientists standing about to impress you with the size of the thing. Most of this bulk, actually, is taken up by a simple electromagnet (Page 111), not nearly so complicated in construc-

tion or action as the transformer the Power Company keeps up on the pole down at the end of your block. The electromagnet does nothing more than produce a strong, steady magnetic field across a gap a foot or so high and a few feet in diameter, at the center of the structure. The bigger this space and the stronger the field across it, the faster the nuclear bullets can be shot. This is the reason the scientists like them big. The largest cyclotron in the world, at the University of California in Berkeley, has a magnetic gap six feet high and more than 15 feet in diameter.

The really interesting things happen in a big flat can, evacuated, that just fills up the magnetic gap. Within this can is another smaller can, cut into two halves that are called "dees," because each one is shaped like the letter D. These dees are connected to a powerful



In a cyclotron, ions are given the high speeds they must have to reach the nuclei of atoms in the target.

high-frequency oscillator (Page 270) which makes first one dee, and then the other, highly negative with respect to its mate. A positively-charged ion—one of the little nuclear bullets—moving around well inside one of the dees will not know whether that dee is positive or negative. But if it comes near the gap between the dees when the other dee is negative, it will be pulled across the gap and will proceed to move along in the second dee, faster than it was moving in the first.

Now it is an interesting and useful fact that an ion moving across a magnetic field moves in a circular path (you recall that this very principle is used in the electromagnetic method of separating isotopes); the faster the ion goes, the bigger the circle. But until the ion is going nearly as fast as light itself, it always takes the same time to get halfway around—the faster ion has just enough extra speed to take it around its longer path in the same time as the slower ion needs to go around its shorter path. This means that the oscillating circuit can be adjusted so that the ion, each time it gets around to the

gap between the dees, finds a strong electric field pulling it across to the opposite dee and speeding it up.

When this adjustment of frequency is made the cyclotron is ready to work. A nuclear bullet, starting near its center, will automatically travel in a spiral path outward, getting a shove forward twice per revolution. These repeated accelerations can bring the ion up to speeds of tens of thousands of miles per second. Finally, after several hundred revolutions, the ion gets out near the edge of the dees, where a negative electrode is placed to give it a hearty pull outward. It then flies clear out of the dees and the surrounding tank, through a thin window, and strikes a target containing the atoms whose nuclei are to be bombarded.

Actually, of course, the cyclotron does not shoot a single bullet at a time. Ions are formed continually in a small electric arc down at the center of the dees, from hydrogen or heavy hydrogen or helium, whichever kind of nuclear bullet is desired; and a continuous stream of projectiles pours out of the window at the edge of the machine. Perhaps you have seen color photographs of such a stream shooting forth into the air, making the air molecules emit their distinctive light as it plows through them. It is an interesting sight, but the physicist usually has some less spectacular target for his nuclear bullets to hit.

VII. *What Are Transuranic Elements?*

Do you recall, from a few pages ago, our little game of making up nuclei out of protons and neutrons and seeing which ones were stable—which ones would last indefinitely after they had been put together? We found, you remember, that we had to be rather careful about the number of neutrons we put in with each number of protons, if we wanted our nucleus to hang together permanently. Now we are ready to have a look at some of the actual results in the field of nucleus-making.

In spite of those practical difficulties that we could overlook when we were running a nucleus factory only in imagination, the physicists have done fairly well. They have made some 500 different kinds of new nuclei, nuclei that are not found anywhere in nature. This is about twice the number of the natural nuclei, so we can say that the "atom-smashing" studies have tripled the number of nuclei available to mankind. All the 500 artificial nuclei are unstable, of course; the nuclei that last indefinitely are already in existence on the earth.

But the artificial nuclei last long enough to be studied and used in various ways, as we shall see. One of them can even be used as the explosive in an atomic bomb!

How are these artificial nuclei made? When we were imagining the process we assumed a supply of protons and a supply of neutrons. Protons are fairly easy to come by: all that is necessary is to remove the electron from a hydrogen atom, and you have a proton left. But neutrons are harder to get and to handle. They normally exist in nuclei, and nuclei have to be disrupted to set neutrons free. Once free, the neutron cannot be controlled by electric and magnetic fields, as protons are, for it has no electric charge for these fields to act on. The neutron flies merrily along, unhindered by the charges on the electrons and nuclei it encounters; occasionally it hits a nucleus squarely and bounces away; and very soon some nucleus takes it in and keeps it. So a supply of free neutrons is impracticable, except in imagination.

Here is how a physicist goes about making artificial nuclei. He starts with stable nuclei, already existing in nature, and he bombards these stable nuclei with nuclear bullets from such a gun as a cyclotron. A nucleus hit by one of these bullets will often take the bullet in; sometimes it merely keeps the bullet, and somtimes it reacts by throwing off another kind of nuclear particle. When either of these things happens, a different kind of nucleus has been made.

For example, the target nucleus might be Cu-63, the bullet might be a fast proton, and a neutron might be given off when the bullet strikes. The resulting nucleus then will contain one more proton and one less neutron than Cu-63. Since the number of protons is changed, the number of electrons around the nucleus must also change, and this means that the new atom is no longer a copper atom. It is, in fact, a zinc atom, with 30 protons and 33 neutrons in the nucleus; such zinc nuclei have been made and studied, and they are found to last about 40 minutes.

For a more complicated example we might think of bombarding Cu–63 with a deutron (this, you recall, is simply a heavy-hydrogen nucleus, consisting of a proton and a neutron stuck together) and getting out a proton. The net result of this exchange is to add a single neutron to the Cu-63 nucleus. It is still copper, since the number of protons stays unchanged at 29, but there are now 35 neutrons in the nucleus. Nature does not accept this number of neutrons to go along with 29 protons, and the new Cu-64 nucleus lasts only about 13 hours.

You can see for yourself that, with several different possible bullets to shoot and several possibilities for the chip that is knocked out of the nucleus, there is much variety in what can be done with a single type of target nucleus. With some 250 stable nuclei to use as targets, it is hardly surprising that some 500 artificial nuclei have been produced, many of them in several different ways.

Almost all these unstable artificial atoms are, of course, isotopes of known and stable atoms. That is, the number of protons in them is somewhere between one and 92, and nature already contains elements whose atomic nuclei have almost all these numbers of protons. So most of the artificial nuclei, though their nuclear properties are new and diversified, form atoms with well-known chemical properties.

The *transuranic* elements you have been hearing about recently have nuclei that contain more than 92 protons, the number that the uranium nucleus contains. Nature goes no farther than 92 protons, so the atoms containing these transuranic nuclei are different chemically from the atoms of any natural element. New names have to be invented for them as they are made, just as the names "oxygen," "hydrogen," "copper" and the like had to be invented for the natural elements when they were first discovered and isolated from one another.

The simplest of the transuranic elements is "neptunium," with 93 protons in the nucleus. It can be made in several different ways, yielding different isotopes. One way is by bombarding U-238 with deuterons and getting two neutrons back out. The total number of particles continues to be 238, but one neutron has, in effect, been replaced by a proton. This isotope is called Np-238.

The next of the transuranic elements, with 94 protons, is called "plutonium." It is an isotope of plutonium, Pu-239, containing 94 protons and 145 neutrons, that can be used as an explosive in atomic bombs.

Several additional transuranic elements, with proton numbers up through 96, have been made, studied, and announced to the general public.

IX. *What Happens When a Nucleus Splits?*

Has it occurred to you to wonder, as we have been discussing neutrons, whether neutrons might not be very useful bullets for shooting at nuclei? The answer is that they are. Being electrically

neutral, a neutron can pass unhindered through the electron cloud and come right up against a nucleus without feeling any repulsive force from its positive charge. It does not have to be fired from a complicated and expensive gun such as a cyclotron. As a nuclear bullet, the neutron has, however, some serious limitations: free neutrons are not easy to produce and are almost impossible to control. The only known source of a free neutron is a nucleus that has just been hit by a nuclear bullet, and the only thing man can do to a free neutron is to slow it down, by letting it bounce about from one nucleus to another in some suitable material. Nevertheless, neutrons have been used as bullets against almost all the stable nuclei, and some interesting and important things have been found out with them.

What happens when a neutron strikes a nucleus? To answer this question we need to know two things: how many protons and neutrons are in the target nucleus? and how fast is the neutron going when it strikes? Even then, there is no formula for telling what will happen. We just have to look up this nucleus and the neutron speed in some Tables and see what happened when the experiment was tried.

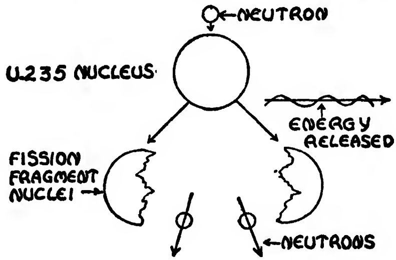
Sometimes the neutron simply bounces away from the target nucleus, making it recoil a little, and losing a little kinetic energy in the collision. Sometimes it loses a considerable part of its energy by stirring up the nucleus internally, but still gets away. Sometimes it jars a proton or another neutron out of the nucleus. Sometimes it is simply taken in, and the nucleus settles down (temporarily, usually) with one extra neutron in it. Such capture of the neutron is especially likely to happen when the neutron is going slowly, but different nuclei are very different in their aptness to take in slow neutrons.

Some nuclei prefer to capture neutrons of a certain speed, rather than slower or faster neutrons. The heaviest natural uranium nucleus, U-238, is an important case of this sort. If a neutron travelling at a certain moderate speed, about a thousand times as fast as a molecule of air at ordinary temperatures, happens to strike a U-238 nucleus it is very likely to be captured, changing the nucleus to U-239. If the neutron is going either faster or slower than this particular speed, its chances of simply bouncing away from the U-238 nucleus are much better.

What about U-235? It was tried (in the natural mixture of uranium isotopes) as a target for neutrons as early as 1934, soon after

the neutron was discovered. Everyone expected that, like other nuclei, U-235 would either capture a neutron striking it (to become U-236) or would throw off one or two nuclear particles and become a slightly different sort of nucleus. Some atoms different from U-235 were formed, all right, when neutrons were shot at U-235, but they did not seem to have just the chemical properties that would be expected for atoms not much different from U-235 in their nuclear contents.

Would it surprise you to know that more than four years of work by some of the most expert scientists was required to solve this little mystery? The answer, when it came, early in 1939, was so simple that everyone blinked and said: "Of course!"



Fission of a U-235 nucleus is caused by neutron impact. Fission produces two fragment nuclei, more than one new neutron (on the average), and release of nuclear energy.

The U-235 nucleus, when it captures a neutron, does not simply settle down or simply throw off a proton or so. It splits right in two! One half is a little larger than the other, and each half contains rather more neutrons than it should, for stability, but otherwise each half is quite a proper nucleus by itself. Each half takes its own share of the 92 protons, so the two resulting atoms have an average of 46 protons each. This means that they are isotopes (unstable isotopes, however) of well-known chemical elements. They are very far from uranium, of course, in their makeup and chemical behavior. It was the unexpected chemical properties of these fragments that posed the mystery in the first place, and it was a careful study of these chemical properties that finally solved it.

So unusual an occurrence certainly deserves a name for itself. The splitting of a nucleus into two halves, nearly the same size, soon came to be known as "fission."

Fission is now known to occur in U-235; in thorium, which has

a single isotope containing 232 nuclear particles; in protoactinium, a very rare element with 231 particles in the nucleus; and in the Pu-239 nucleus of the transuranic element plutonium. In U-235, a very slow neutron is most likely to cause fission, though a neutron of any speed is able to do the trick if it is captured. Neutrons are not the only bullets that will cause fission: deuterons and gamma rays (Page 286) have also been tried successfully.

If this were the end of the story about fission, you would be justified in wondering what it has to do with atomic power and atomic bombs. But there are two more things to be told, and these, as you will see, make the fission business begin to look rather interesting from a practical viewpoint.

In the first place, the two halves of the splitting U-235 nucleus—or plutonium or thorium or protoactinium nucleus—fly apart with tremendous speeds, plowing their way through the surrounding material. The energy set free by the nucleus when it splits, and carried away mostly by these two flying fragments, can be measured quite precisely. It turns out to be many times as large as the energy set free in any other known nuclear reaction. To say how many ergs or kilowatt-hours are released by each nucleus would not be very informative. A comparison is easier to grasp: if all the nuclei in a pound of U-235 should split, they would release as much energy as is set free by burning 1250 tons of coal, or by exploding 10,000 tons of TNT.

The second important fact is that the two half-nuclei are not the only debris from the explosion. In addition, a few neutrons are set free and leave the scene at high speed. There are not many of them—the average is somewhere between one and three per fission—but on the average they certainly outnumber the *one* neutron that is required to trigger off the nuclear catastrophe.

Perhaps you can see for yourself why this yield of several neutrons per fission is so significant. At any rate, if they did not come out you would probably never have heard of an atomic bomb except as the dream of some comic-strip artist.

IX. *How Is Atomic Energy Stored Up?*

Since the bomb exploded in Hiroshima, "Einstein's Principle of the Equivalence of Mass and Energy" has often been mentioned in the newspapers and magazines and over the radio. Unless you have led a very secluded life you must have heard of it by this time. But

do you really know what the phrase means, or is the idea still slightly hazy to you? Perhaps you would welcome a little discussion of the matter—not a thoroughgoing explanation (that would be beyond the scope of this book) but just enough to show what the words mean and what the principle has to do with atomic bombs and atomic energy.

The principle, actually, is no war-born novelty. Einstein proposed it more than 40 years ago, and it was tested and thoroughly proved about 20 years later, in the very early days of the atom-smashing work. We might look back among those experiments for many examples to illustrate it. Instead, however, let us consider a more homely and familiar situation.

Suppose you lock up one pound of inert material—any kind of material—in a box with special walls that will not let any kind of energy enter or escape. Then, says Einstein (and today practically everyone, looking over the evidence, is bound to agree with him), you can say either that you have one pound of material in the box, or that you have 11.4 billion kilowatt-hours of energy in the box. If sometime later you peep in and find the material is flying about in the box instead of lying on the floor as you left it, then the material is no longer a full pound, but a little less. Whatever kinetic energy the material has acquired it must have paid for with part of its mass, at the rate of one pound for 11.4 billion kilowatt-hours. If this idea of an inert substance suddenly taking off by itself and flying about sounds strange to you, just imagine the pound of material you put in the box was a skyrocket with a little clockwork to set it off after you shut the top down. If the pound of material is all gone, then in its place you will find just 11.4 billion kilowatt-hours of energy in some form—light waves, x-rays, or motion of the molecules in the air or in the walls of the box. By the way, if you have any reason to expect that any large fraction of the pound has been converted into energy it would be well to open the box with caution, for 11.4 billion kilowatt-hours is approximately the energy set free in burning up a million and a quarter tons of coal.

From this illustration, you can see that the principle means just what it says: mass and energy are equivalent; when either one disappears the other always appears; and the rate of exchange between the two is 11.4 billion kilowatt-hours per pound.

Now let us think of a splitting U-235 nucleus. Before the neu-

tron comes along it is a placid thing, with only a little energy of motion. The neutron adds little energy to it, almost none if it be a slow neutron. Yet, when the U-235 splits, the two half-size nuclei and the few spare neutrons leave the scene of the fission with tremendous kinetic energy. We must say, then, that some of the mass of the U-235 nucleus and the neutron it captured must have been converted into energy of these flying fragments. If we could collect all the pieces after they have frittered away the energy and have come to rest, we ought to find that, all together, they have less mass than the original U-235 nucleus plus the original neutron.

This very measurement of mass can, in fact, be made. The result agrees with the Einstein Principle as well as one could wish. The fission fragments, all together, weigh about one-tenth of one per cent less than the original U-235 and the lone neutron that struck it. This small decrease in mass is just enough, when multiplied by the universal conversion factor of 11.4 billion kilowatt-hours per pound, to account for the observed energy release.

Perhaps you still want to put your finger on *something* specific that has disappeared. What about the particles—are they still all there? Yes, they are. The 92 protons and the 144 neutrons are all present. We have to say that the mass of *each* particle is about one one-thousandth less in the half-size nuclei than in U-235. Strange as this may sound, it has to be accepted, and with a little thought we can convince ourselves that it is all right, after all. When the particles are crowded together in large numbers, as in the U-235 nucleus, they have a potential energy which is stored up in the form of mass; when they are in the smaller fission-fragment nuclei they have less potential energy, and correspondingly less mass.

If you insist on going any farther with it, we shall soon run squarely up against one of those unanswered questions stated early in this Chapter: what holds a nucleus together, anyhow? Maybe soon it will be understood, but just now it is still largely a mystery. Meanwhile, however, it is perfectly safe to rely on Einstein's principle that mass and energy are not as different as they seem, and that sometimes one can be bartered for the other, at a fixed rate of exchange. Fission, and the atomic bomb itself, are only the latest in a long series of events that have uniformly supported this striking principle, which Einstein boldly proposed years before there was any experimental evidence to suggest it.

X. *What Is a Nuclear Chain Reaction?*

Have you ever wondered just why a match flame, or the flame of a gas stove burner, keeps blazing away at a steady rate? You know, of course, that the fuel—the match stick or the gas—contains molecules made of hydrogen and carbon atoms, and that combustion is a process of tearing these molecules apart and uniting them with oxygen atoms from the oxygen in the air. The resulting molecules, chiefly water vapor and carbon dioxide, have less energy per atom than the original molecules. It is the energy difference, some of which is liberated as heat and light, that makes a flame such a useful thing.

But how does the flame keep ticking along? Before the hydrogen and carbon and oxygen atoms can unite, they have to be set free from the original stable molecules of fuel and air. To tear up one of these stable molecules takes energy. Where does this energy come from?

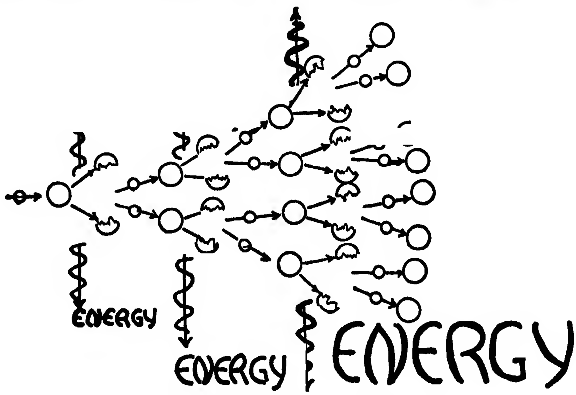
It comes, as a matter of fact, from the combustion itself. Whenever one of the new molecules is formed, it gives out more than enough energy to set the stage for the formation of one more new molecule. On the average, each new molecule delivers to the fuel and to the air, in the form of heat and light and molecular motion, enough energy to spring loose from their moorings the atoms that are required to replace this molecule by another one like it. You can see for yourself that the process, once started, will keep on going, since each generation of new molecules produces another generation just as numerous as itself. It is what is called a *self-sustaining chain reaction.*

This energy transfer from the burning material to the material about to be burned is the essential action in any flame or fire. The energy that escapes, though you may find it very useful for lighting your pipe or keeping the bacon sizzling, is strictly a byproduct.

In a flame, the reaction goes along at a constant rate because the product gases have to be moved out of the way and new oxygen and new fuel have to be brought up to the scene. If the oxygen and fuel are already mixed together, the reaction can go ahead with almost explosive violence—this is what happens in a shotgun shell or in the cylinder of your automobile. Sometimes the energy that propagates the reaction is in the form of a shock wave, instead of heat or light; this is the case when TNT detonates in a bomb. But always, the essential condition for a self-sustaining chain reaction is the same:

each individual reaction must, on the average, produce one descendant of its own kind. If there are more than one, the chain can branch and can fan out violently under the right conditions. But if there are fewer than one, on the average, the race soon dies out and the reaction stops.

Up to now, man has succeeded in producing only one kind of *nuclear* chain reaction, the kind that is used in the atomic bomb and in the other arrangements for releasing atomic energy. The unit reaction, in this chain, is the fission of a nucleus of U-235 or plutonium. The links from each generation of fissions to the next are the few neutrons—between one and three, you recall, on the average



An expanding fission chain reaction, such as occurs when an atomic bomb explodes.

—that are set free by each nucleus when it splits. If just one of these newly-liberated neutrons comes up against another fissionable nucleus and makes it split, then the reaction goes along at a constant rate. If more than one of them succeeds in causing other fissions, the reaction will build up very rapidly from a small beginning to a tremendous rate—it takes only a microsecond or so for a fast free neutron to collide with many atomic nuclei, and much less time than this for a nucleus to split after it has captured a neutron. But if less than one neutron from the average fission succeeds in causing another fission, the chain just as rapidly dwindles down to nothing and the reaction does not sustain or multiply itself. As you can see, a fission chain reaction is not much different from the chemical chain reactions that go on all around us every day.

To make the fission chain reaction proceed, those few neutrons

per fission have to be carefully saved from any other fate that might befall them, and used to cause other fissions. If there are non-fissionable nuclei about that are likely to capture free neutrons, these impurities have to be removed. U-238, as you remember, is such a nucleus—it is very apt to snap up a neutron going at a certain speed, without splitting. If a U-235 bomb is to work, most of the U-238 must be got out of the way. Finally, the lump of material that is to be the scene of the reaction has to be bigger than a certain *critical size*. If it is too small, too many of the neutrons will fly clear out of it and be wasted. This critical size is not microscopic, as you might at first suppose. Nuclei are such small things, and are relatively so far apart, that a free neutron can go for an inch or so in a solid metal before it hits a nucleus.

XI. *How Does an Atomic Bomb Explode?*

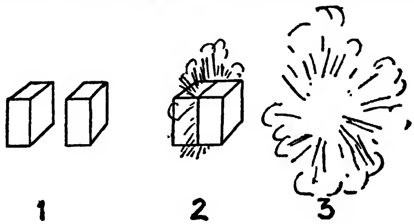
It is still a secret, of course, just how an atomic bomb is constructed. But we can understand what happens when an atomic bomb explodes, even though we have to be a little vague about its size and shape and how the parts are fitted together.

Imagine, then, a lump of metal, either U-235 or plutonium, well purified to free it of atoms whose nuclei are apt to capture free neutrons without splitting. You can think of the lump as the size of an orange or the size of a football, or as large as you please. Actually, it is at least large enough so that a neutron starting out at its center will be fairly certain to hit a nucleus and cause a fission before it reaches the outside. That is, the size of the lump is more than the *critical size* we have just been discussing.

Now imagine that, somewhere inside the lump, a nucleus splits in two. The two nuclear fragments fly apart at great speed, knocking metal atoms out of their way and leaving a trail of agitation behind them. The neutrons that are released bounce into other nuclei and cause them to split, and these in splitting release more neutrons which cause still more nuclei to split. The whole process builds up faster than you can think about it. Almost instantly, the whole placid lump of metal is changed over into a seething disorganized swarm of flying nuclear fragments and flying atoms that these fragments have struck. To put it another way, the energy released by the splitting nuclei converts the bomb into a body of highly compressed gas at a very high temperature. This gas, expanding rapidly, shoves the surrounding air outward and so starts

off a "blast wave." The blast wave does the desired military damage over a wide area.

What sort of fuze is used? The answer is simple: no fuze is needed. Nothing can stop the bomb from exploding as soon as it is made. It takes only one free neutron to start the explosive chain reaction, and there are always a few free neutrons flying about in the



An atomic bomb is made by bringing together rapidly two or more pieces of uranium or plutonium, each one too small by itself to explode.

air anywhere. The only way to keep the lump of bomb metal from exploding is to keep it broken up into small pieces, two or more pieces, each one small enough so that a neutron starting out inside it will have a good chance of flying clear out of the small piece before it hits one of the nuclei it can cause to split. The thing is entirely safe and inert so long as this is true, for then the chain reaction cannot build up. But when the pieces are brought together to form one lump, big enough so that on the average at least one neutron from each splitting nucleus is halted by another nucleus and causes it to split, then the explosion is sure to occur right away.

The bomb, then, is "made" and exploded all at the same time, when the separate pieces of bomb metal, each one too small by itself to explode, are brought together to form one lump larger than the critical size. The pieces have to be brought together very suddenly, of course, for if the chain reaction starts while they are still not intimately together they will be blown apart again by the first beginning of the explosion, and the main part of the explosion will not occur. To put it briefly, the atomic bomb is a dud unless it can be assembled before it has time to explode. How to bring the pieces of bomb metal together suddenly and intimately was according to the Smyth Report, one of the most difficult problems in the design of the bomb. Smyth suggests as a possible method that one piece of bomb metal might be shot into contact with another.

The explosion of an atomic bomb, as you see, is not very dif-

ferent from the explosion of any other demolition bomb. It is a release of a large quantity of energy in a very small space and a very brief time. It does most of its military damage by a blast wave started in the surrounding air.

Still, we can list some differences. The atomic bomb explosion involves a nuclear reaction, while in an ordinary explosion it is the electrons that are concerned, while the nuclei are unaffected in structure. The chain reaction in the atomic bomb explosion is carried along by free neutrons, while an ordinary explosion is propagated by heat or light or shock. An ordinary bomb is quite safe until it has been fuzed and the fuze has been armed and fired, but an atomic bomb cannot exist more than a tiny fraction of a second—it has to be made on the spot by bringing together very quickly two or more pieces of the bomb metal, each piece by itself being too small to explode. Finally, there is a vast difference in the intensity of the explosion: every pound of nuclei that split gives out as much energy as is released by exploding 10,000 tons of TNT.

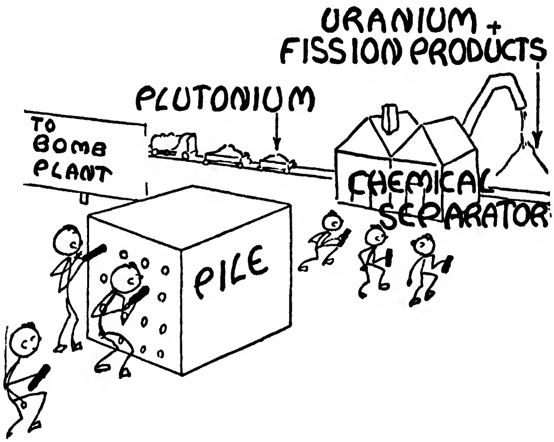
XII. *What Is a Pile?*

The common word "pile," which already had so many different uses in our language, took on a new and specialized meaning in the course of the atomic bomb work. A pile, nowadays, is a sort of nuclear factory. The raw material and the fuel to run the factory are both put in together in the same package, a rod or "slug" of ordinary uranium metal. The factory turns out two chief products. One is energy, in the form of heat. The other is the transuranic element plutonium, which can be used as the explosive in atomic bombs. Which of the two you consider the more important depends on the circumstances. During the war, several of these nuclear factories were built and operated, in the State of Washington. Plutonium for bombs was, of course, the primary product. The heat energy was dumped into the Columbia River to get rid of it. In addition to these two main products, plutonium and heat, the pile yields as byproducts a large number of unstable elements that have many uses in science, industry and medicine. It can also be arranged to shoot out a torrent of free neutrons or a dense flux of gamma rays.

Would it surprise you to know that these nuclear factories contain no rotating parts—no belts or gears or turning shafts? They are quiet, too; not a sound comes out of them. There are no workmen laboring inside. Each factory is surrounded by a thick con-

crete wall, and the workers take care to stay well outside this wall while the plant is running.

In construction, the pile is just what its name would suggest. It is a huge block of graphite—graphite, you recall, is a form of the element carbon, and you see it every day in the lead of an ordinary pencil. Through this graphite block run many small parallel channels. Most of the channels are filled up with slugs of uranium metal, encased in tight-fitting aluminum cans. A few channels are occupied by long rods of the metal cadmium or of a special steel containing the element boron. These rods are for control: when they are



A very schematic diagram of a uranium-graphite pile and its associated chemical separation plant, for producing the transuranic nuclear explosive, plutonium.

pulled out farther the factory runs faster and hotter; when they are pushed all the way in the factory stops working and begins to cool off. Water is flowed through the channels, past the uranium slugs, to take away the heat as it is generated.

Inside each slug, some of the U-235 is slowly used up by fission, being changed into the unstable medium-sized nuclei that we have mentioned as important byproducts of the nuclear factory. The heat energy set free by fission flows out of the slug into the surrounding water and is pumped away. While these things are going on, some of the U-238 in the slug (you recall that these slugs are unseparated uranium, with 140 times as much U-238 as U-235 in the mixture) is slowly changed into the transuranic element plutonium, the material whose nuclei have explosive properties like the nuclei of

U-235 itself. When enough plutonium has accumulated in a slug, the slug is removed from the pile and the plutonium is separated from the uranium and the various byproducts by chemical methods.

Neutrons, as you might expect, are involved in all these nuclear changes. In fact, a pile in operation is a real inferno of flying neutrons, each neutron released from a splitting nucleus and on its way to lodgment in some other nucleus. Free neutrons are more plentiful in an operating pile than anywhere else on earth, except in an exploding atomic bomb. In the pile, as in the bomb, the neutrons are used as links in a self-sustaining nuclear chain reaction. The reaction is the same in both cases. But in the pile it is controlled to run along at a fixed rate, while in the bomb it is encouraged to run away with itself as fast as it can.

Probably you see several things to wonder about. Why have the big block of graphite? Why not just heap up a big mound of pure uranium and let it stew along by itself? And if a self-sustaining fission chain reaction will occur in the natural mixture of uranium isotopes, why bother to separate out U-235 or manufacture plutonium? Why not just make the bombs out of unseparated uranium metal? As for plutonium, how can a nucleus with 94 protons in it possibly be made by exposing U-238, which has only 92 protons in its nucleus, to bombardment by uncharged neutrons?

These are all sensible questions. You may be sure, though, that there are sufficient answers to all of them. No one, especially in time of war, is interested in getting his explosives the hard way. If the bombs are made of U-235 or plutonium, it must be that the cheaper and more available natural mixture of uranium isotopes simply cannot be made to explode. And if the graphite block were not an essential part of the pile structure, it certainly would have been omitted.

Let us look at the last question first. How can neutron bombardment of U-238 produce plutonium, which has two more protons in its nucleus than uranium has? Where do these two extra protons come from?

To find the answer, we have to go back to our imaginary game of making up nuclei out of single protons and neutrons and seeing how long each one of our creations would last. You remember that if we got the right number of neutrons to put with a given number of protons, the nucleus would be stable. Sometimes—more often than not, in fact—we had a little latitude in our choice for the number

of neutrons. But if we chose wrong, our nucleus would be unstable. It would last for a while, but not indefinitely.

What happens to an unstable nucleus when it stops "lasting?" Does it blow all apart, or does a proton or neutron fly out of it to leave the nucleus a little smaller, but with the right proportions for stability? Neither of these things happens, actually. What does happen is very surprising, at first glance. If the nucleus contains more neutrons than it should for stability, one of the neutrons eventually *changes* suddenly into a proton. To do this is has to acquire a positive charge, just equal in size to the negative charge on an electron. The nucleus provides this positive charge for the neophyte proton by manufacturing (somehow—no one quite understands this bit of the business) a negative electron and throwing it away. The electron is usually ejected at high speed, so fast that it can go for several inches in air before stopping.

If the protons are in excess, one proton eventually changes itself into a neutron. There are two ways of doing this. Usually the nucleus makes and ejects a high-speed positive electron (a "positron"), quite like the ordinary negative electron except for the sign of its charge. Sometimes, however, the nucleus manages to capture one of the negative electrons that are whirling around it. Whether the nucleus sends out a positive electron or takes in a negative electron, in either case it has provided the electricity necessary to change one of its positive protons into an uncharged neutron.

If a single change of a proton into a neutron, or its reverse, is enough to bring the nucleus to stable proportions, it settles down permanently after making this single change. But sometimes the original nucleus is so far from stability that several changes are necessary before it reaches one of the proportions that Nature tolerates. When this is the case the required changes occur, one after another.

If the unstable nucleus is a heavy one—if it contains more than 83 protons—it may make a step toward stability by throwing off an alpha particle, consisting (as you will recall from Page 286) of two protons and two neutrons. But alpha-emission occurs only with these heavy nuclei. The proton-neutron or neutron-proton conversion is a much more usual treatment for curing nuclear instability.

Do these spontaneous changes within a nucleus seem strange and unexpected to you? You can comfort yourself with the knowledge that they seemed just as strange and unexpected to the scientists who first discovered them. Long acquaintance with many cases of them

has made these changes more or less familiar, but there is still no satisfactory explanation of how they occur.

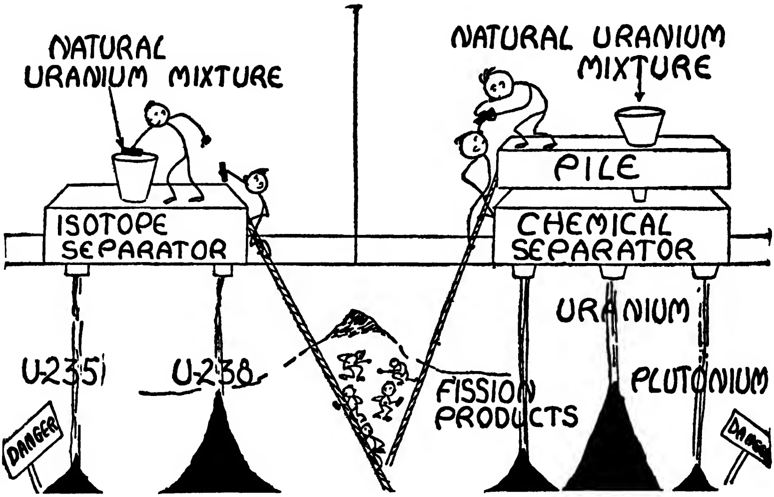
Now we can go back to the U-238 nucleus, just as it is in the act of capturing a neutron. The nucleus, after the capture, becomes U-239. It is unstable with the extra neutron in it. It soon starts to rectify matters by throwing out a negative electron to change one of the neutrons into a proton. The nucleus then contains 93 protons, so the atom is chemically different from uranium. It is, in fact, one of the isotopes of the first transuranic element, neptunium. But Np-239 is still unstable. It soon emits another negative electron, changing another neutron to a proton, and becomes an isotope of the second transuranic element, plutonium. This plutonium nucleus, Pu-239, is not quite stable. In the course of a long time it would emit an alpha particle. But it lasts long enough to accumulate in the uranium slugs in a pile, to be extracted from the slugs, and to be used as the fissionable filler of atomic bombs.

The fact that plutonium is chemically different from its grandparent uranium and from all the middle-sized fission fragments means that it can be separated by chemical methods from these other contents of a slug, after the slug is taken out of the pile. Chemical separation is much easier, cheaper and faster than the complicated isotope-separation methods that are needed for getting the other atomic bomb explosive, U-235, away from its chemical twin U-238.

Next, why is the big block of graphite necessary? Perhaps you recall that the few neutrons that come out of a splitting U-235 nucleus are travelling at high speed; and that a U-238 nucleus is most likely to capture neutrons travelling in a certain intermediate speed range; and that U-235 is most likely to capture a neutron, and be split by it, when the neutron is going very slowly. Put these three facts together and you can begin to see a reason for the graphite. It will not do to let the fast neutrons slow down by bouncing from one uranium nucleus to another in a block of solid uranium, for they will almost certainly be captured by U-238 as they slow down through the critical speed range where such capture is very likely. And the chain reaction, you recall, cannot sustain itself unless at least one of the neutrons from the average U-235 fission gets to another U-235 nucleus and makes it split. The graphite furnishes a place for the fast neutrons to slow themselves down past this critical speed range without being captured. After they are going slowly enough, they can be let back into the uranium slugs. Each slug, then, is con-

tinually sending fast neutrons out into the surrounding graphite and is receiving slow neutrons from the graphite in exchange. The U-238 still captures some of the neutrons, of course—it is just this capture that leads to the desired end-product, plutonium—but enough neutrons get back to U-235 nuclei to keep the chain reaction ticking along.

Graphite is not the only material that might be used. There are several other substances whose nuclei will slow down neutrons effectively without capturing them. But graphite, when the plutonium



With natural uranium as the raw material, two nuclear explosives can be made. On the left, U-235 is picked out from U-238 in an isotope separator. On the right, plutonium is made from U-238 in a pile, and is then purified in a chemical separation plant.

piles were constructed, was the most readily available material with the necessary nuclear properties. Heavy water can be used. In fact, heavy water is better in some ways than graphite for the purpose—you see now why a Nazi plant producing heavy water might be worth bombing—but it is rather less plentiful and cheap than graphite.

The problem of keeping the nuclear factory running at a set level of production turns out to be very simple. The sliding control rods contain nuclei, such as those of cadmium and boron, which capture neutrons very readily. If the pile starts freeing neutrons too

copiously, a little more of the rod can be pushed into the pile to soak up the extra neutrons and keep them from multiplying out of bounds. If the pile becomes sluggish the rod can be pulled out a little to let the number of free-flying neutrons build up. The control can, in fact, be entirely automatic, the rods being moved in and out in response to an instrument which keeps track of the density of the "neutron gas" within the pile.

Finally, why does a pile need to be so big? Why not make a little basement-size model for heating a house in wintertime? One answer, of course, is that a large quantity of uranium yields only a little plutonium and yields it only slowly, so if plutonium is needed rapidly in large quantities for atomic bombs the factory has to be big enough to handle a large quantity of uranium at once. But there is another reason, even more essential. The pile, like the atomic bomb, simply will not work unless it is bigger than a certain critical size. Even with the most ingenious design, the fission chain reaction in ordinary uranium barely manages to keep going. If too large a fraction of the neutrons is wasted by leakage out of the surface, the chain reaction cannot sustain itself. There is no material that can be used as a container to hold the free neutrons inside the pile. The only way to make the surface leakage unimportant is by putting most of the interior of the pile a long way from its surface—and this means, of course, that the pile has to be large. Also, for protection of personnel, the pile has to be surrounded by thick shielding walls, which add considerably to its bulk.

XIII. *What Are Tracer Atoms?*

Perhaps you have been wondering what practical uses there are for the unstable nuclei, those odd specimens of nuclear architecture that do not quite satisfy the exacting requirements of Nature. It is interesting, of course, that so many of them can be made—roughly 500 different ones, you recall, as compared with the 250 natural stable nuclei. Their methods of becoming stable, by changing a neutron to a proton or a proton to a neutron, are certainly curious and unexpected. But what are they good for, anyhow?

Let us see a little more about these man-made nuclei. We might take the unstable sodium nucleus Na-24 as a specific example. This nucleus can be made in some five different ways, by shooting various nuclear bullets at various stable nuclei. It contains 11 protons and 13 neutrons, too many neutrons for stability. It becomes stable by the

usual method of changing one of the neutrons to a proton, throwing out a fast negative electron when the change occurs, and settles down permanently as a magnesium nucleus. Na-24 lasts about 15 hours.

We need to look a little more closely into this matter of lifetime. To say that a Na-24 nucleus lasts roughly 15 hours is a bit misleading: it suggests that all Na-24 nuclei change at the same time, roughly 15 hours after they are made. This is not at all what happens. The instant when a particular Na-24 nucleus will make the change is quite uncertain. It may change within one second after it is made, or it may still be unchanged a billion years later. The only thing certain is that a definite fraction of the nuclei will change in each second, no matter how long ago or how recently the batch was prepared.

All the unstable nuclei decrease in number according to this same simple rule. Each different nucleus is characterized by a certain *half-life,* the time it takes for just half the nuclei in a given batch to change to stability. Half-lives ranging from fractions of a second to thousands of years have been observed. Na-24, with a half-life of 14.8 hours, is a moderately long-lived nucleus, as these things go.

The fast negative electron thrown out by a changing Na-24 nucleus can be detected by means of the ionization it causes in flying through a gas, such as air. These fast electrons can actually be counted, one by one, as they speed away from their parent nuclei.

Each Na-24 nucleus, while it is waiting to make the final change, is a perfectly good nucleus for a sodium atom quite like any other sodium atom in its chemical properties. If you have a little batch of Na-24 atoms you can, for example, use them to make sodium chloride (table salt) or any other sodium compound you wish. So long as the nucleus has just 11 protons the atom will follow along with its chemical twins in whatever chemical processes you choose to put them through.

Now suppose you are a physiologist and are curious to know how long it takes sodium, eaten as table salt, to get from the mouth into the blood stream and finally out to the fingertips. It is a simple problem, if you have some salt containing Na-24, and one of the counters for fast electrons. You will simply dissolve the salt in water, drink it down, and then stand with your fingers on the counter. After a minute or so (it happens surprisingly fast) the counter will begin to register the arrival of fast electrons, shot out through the skin of your fingers from Na-24 nuclei that have got just that far when their turn comes to change. You know that

ordinary sodium atoms would have taken just the same length of time to make the trip, for the body has no way of telling whether a sodium atom is stable or unstable. The Na-24 has served as a *tracer* to tell where ordinary sodium goes, and how fast.

This is a simple problem, but if you think about it a little (recalling that the blood contains so much ordinary sodium that any stable sodium atoms put into it would immediately be lost in the crowd) you will see that it could hardly be solved by any other means.

There are hundreds and thousands of such applications, in many fields of research and industry, for these unstable tracer atoms of the 92 different chemical elements—atoms that go along quietly with their stable fellows until the moment of their doom arrives, and then proclaim their presence by sending out particles that can be detected. Sometimes the job can be done in no other way; sometimes tracer atoms are used because the tracer method is quicker or more convenient than any alternative method.

What about the medical applications? The possibility of following a chemical element in its course through the normal living body, without upsetting the delicate chemical balances that the body maintains, is perhaps the most important contribution of the unstable-nucleus tracer method to medicine. Minute quantities of tracer material can be used, far too little to harm the body by the particles sent out, since the detection equipment is capable of counting single atoms as they change.

But there is even a possibility of treating some diseases directly by means of unstable nuclei. Iodine, for example (this is the case that has been most studied), tends to concentrate in the thyroid gland, in the throat. For certain thyroid diseases, treatment with radiations to bombard the gland tissue might be recommended. An x-ray machine might be used, or a radium or radon capsule (Page 287). But another method might be to feed the patient an iodine compound containing a considerable proportion of unstable iodine atoms. These unstable atoms would be concentrated, along with the ordinary iodine, into the thyroid. As each unstable nucleus changes, the electron and the other radiations it sends out will bombard the ailing tissue right on the spot. The bombardment will taper off in intensity as the unstable atoms decrease in number, and after a few days it will have sunk down to a negligible rate.

This description of this method of treatment is intentionally

cautious, for these things are still in the experimental stage and the doctors are not yet sure how widely and how effectively the method can be used.

Incidentally, an unstable nucleus at the instant it changes to a stable nucleus usually emits, in addition to the positive or negative electron or alpha particle, a little batch of energy in the form of a penetrating gamma ray (Page 286). These gamma rays are the "other radiations" mentioned in the preceding paragraph. Sometimes it is the gamma ray and not the fast charged particle that is detected as evidence that a nucleus is in the act of changing. The interior of a pile in operation contains, in addition to the "gas" of free-flying neutrons, a tremendous flux of gamma rays given out by the unstable fission-fragment nuclei as they settle down toward their final stable construction. The shielding around the pile is designed to absorb both the gamma rays and the neutrons. Without the shielding, the pile would be a lethal machine for anyone coming near it.

The unstable half-size nuclei that result from fission of U-235 or plutonium can, of course, be used as tracers. But a pile can also be used to manufacture unstable tracer atoms of almost any other element. All that is necessary is to put some of the element into the pile, let the neutrons batter away at its nuclei for a while, and then remove it and separate the desired unstable atoms from the other products formed by neutron bombardment. Many of the useful unstable atoms can be made more conveniently and in much greater quantities in a pile than by any of the other possible methods, such as using a cyclotron to shoot charged nuclear bullets at nuclei.

Carbon is one of the most important elements in all of chemistry. As you know, almost all the molecules that make up living cells, in animals and plants, contain carbon atoms. Physiologists and chemists have long wished for some way of following this element in its course through the life processes and through the complicated reactions of organic chemistry. Before the war it was possible to make, with the cyclotron, small samples of an unstable carbon isotope, C-11, having a half-life of only 21 minutes. So short a half-life calls for speed and ingenuity in making experiments; nevertheless, some interesting work was done with C-11. For example, the formation of carbohydrates in plants, from the carbon dioxide of the air, was studied. Now it appears that a long-lived unstable carbon isotope, C-14, can be made readily and in large quantities in an operating pile, by putting a suitable nitrogen compound into the neutron flux. C-

14 has a half-life of about 1000 years—long enough for many experiments that are out of the question with C-11. We may expect that C-14 will be one of the most useful of the tracer atoms the piles will be called upon to supply.

XIV. *What Is the Future of Atomic Power in Peacetime?*

In the war years, plutonium for bombs was the only important product of the nuclear factories. The heat that was generated in the controlled fission chain reaction in an operating pile was an unwanted commodity, to be got out of the way as conveniently as possible.

But if a steady flow of atomic energy for peacetime purposes is needed, the heat rather than the plutonium becomes the important product of an operating pile. It would be convenient if someone could discover a way of getting the fission energy out in some other form than heat, but as this is written the hope for such a discovery is dim, and the engineers are facing the problem of using the heat from the pile to turn a shaft.

It is an old problem, of course. What is required is some kind of heat engine (Page 200), such as a reciprocating engine, a turbine, or a reaction motor. But any heat engine, as you recall, wastes most of the heat that comes into it, unless the source of heat is at a very high temperature. If atomic energy from a pile is to be used efficiently the pile has to run very hot—much hotter than the water-cooled piles that were designed for plutonium production. The design of a high-temperature pile presents many new problems, which are now under study.

The size of a pile using the natural mixture of uranium isotopes is embarrassingly large. You remember that the fission chain reaction, even with the best design and the purest materials, simply will not keep going unless the pile is so big that the average free neutron finds it nearly impossible to reach the surface and escape. The critical size can be reduced by using "enriched" material, containing some plutonium or some extra U-235. In fact, an atomic bomb can be considered as a power pile of the smallest possible size, needing only some suitable control mechanism to keep the chain reaction in it ticking along steadily instead of building up explosively. But, however small the pile proper, the thick and heavy shielding walls are still necessary. You need not expect, any time soon, to be driving your automobile by atomic power. The first atomic power installations,

as it seems now, are likely to be huge piles furnishing heat to heat engines of some kind, which will turn electrical generators just like the generators that are now turned by steam or water-power. The electrical energy will, of course, be distributed over the usual network of transmission lines.

How big is the stockpile of uranium? How long will it last? The estimates are all uncertain, and they vary widely. The Smyth Report quotes one estimate that the uranium in known deposits of ore is enough to supply the power needs of the United States for 200 years.

How will atomic power affect our daily lives? Prophecy on such matters is notoriously risky. But here is another question you might consider, which is free of all the mystery and glamor attaching to the words "atomic power." Suppose someone should discover that ordinary water can be burned just like fuel oil, provided you use a special sort of furnace as big as a bungalow and costing about a million dollars: how much would that discovery affect your daily life? If you are a coal miner or a dealer in fuel oil, you might be a little worried about the future of your job, but otherwise you would probably take the news calmly.

After all, you would tell yourself, power is not the only item in the picture. The things you want and need are made of raw materials; they involve some workmanship; and they have to be distributed. Certainly you would not expect them to flow toward you in endless quantity, even if someone had invented a workable perpetual motion machine for turning all the wheels of industry. Many experts predict, in fact, that our daily lives will be affected more quickly and perhaps more deeply by the results of studies that can be made with the byproducts of an operating pile—the tracer atoms and the streams of neutrons and gamma rays—than by atomic power itself.

Before we close this Chapter, a word about other possible sources of atomic power is in order. The fission chain reaction is the only self-sustaining nuclear reaction that man has been able to set going. But our sun and the other stars, it is now believed, stay hot because they are continually supplied with atomic energy from a nuclear reaction raging inside them. This reaction is one which builds up nuclei, instead of splitting nuclei into smaller parts. It is a rather complicated reaction, which has the net result of assembling four protons into an alpha particle—that is, it changes hydrogen into

helium. Perhaps someday this reaction can be set up on a small scale here on earth. But the present prospects for it are not bright.

The fission reaction, you recall, converts only one one-thousandth of the mass of the uranium or plutonium nucleus into energy. Is there any chance of converting *all* the mass of some nucleus into energy, and thus making an atomic bomb or an atomic power plant that is a thousand times as powerful, pound for pound, as those we have now? In principle, it is possible. But no one has yet succeeded in converting all the mass of even one proton or neutron into energy, and the dream of finding a chain reaction which will do the complete conversion automatically on a large scale is indeed a distant dream.

It may surprise you, though, to know that units of mass are being completely converted into energy in the air around you as you read this. The units of mass are ordinary electrons and positive electrons, or positrons. The positrons are created in the air by the mysterious cosmic rays that pour in on the atmosphere from outer space. When a positron has slowed down it eventually bumps into an ordinary negative electron somewhere. The two charges cancel each other; and the two particles disappear completely. Their mass is replaced, according to the Einstein Equivalence Principle, by the energy of two gamma rays that leave the scene of the collision in opposite directions with the speed of light.

QUESTIONS AND ANSWERS

Now that you have finished reading the book, how much do you know? You can test your knowledge on the questions that follow. Not all of the questions are easy to answer. Some will require considerable thought and deduction, but all are based on the physical principles that you have learned.

There are three sets of questions, as follows: (1) Fifty questions in which you are to choose one of several possible answers. Only one of the statements following the numbers in parenthesis is appropriate. The others are incorrect or inappropriate. Score two points for each answer that you choose correctly. (2) One hundred "true and false" statements. You decide whether each statement is true or false, then score one point for each correct answer, zero points for each question that you fail to answer, *and subtract one point from your total for each incorrect answer.* (3) Fifty questions that require a short statement for an answer. Score two points for each question that you answer correctly.

If you have learned your lesson well, you should make a score of at least sixty points out of a possible hundred on each set of questions. Eighty per cent is excellent.

Answers are given on page 374.

"Choice" Questions

One of the statements following the numbers in parenthesis is appropriate. The others are incorrect or inappropriate.

1. If you and your butcher had agreed to use the metric system, when you asked him for a roast of beef he would be likely to show you a piece of meat weighing (1) 3 kilograms, (2) 100 kilograms, (3) 3 milligrams, (4) 100 grams.
2. If you were traveling by automobile in Mexico and found yourself nearly out of gasoline, you would ask the attendant for about (1) 12, (2) 20, (3) 45, (4) 65 liters of petrol to fill your 12-gallon tank.
3. If your speedometer read 50 kilometers per hour while you were motoring through the French countryside, your wife would be

likely to call out from the back seat, (1) "Step on it, John; we'll never get back to Paris," (2) "Don't drive so fast; I can't see a thing," (3) "Isn't this delightful?"

4. According to Newton's Second Law of Motion, (1) doubling the acceleration of a body halves the required force, (2) doubling the force acting on a body doubles the acceleration, (3) a body without any force acting on it continues to move in a straight line, (4) the momentum of a body is proportional to the mass of the body.
5. A barrel half full of water weighs 50 pounds. If 10 pounds of live fish are thrown into the barrel (assume that none of the water spills out), you know that the scales will now read (1) 60 pounds, (2) 50 pounds, (3) between 50 and 60 pounds, (4) less than 50 pounds.
6. If a sailor carelessly drops a monkey wrench from the top of the mast of a moving vessel, he will probably call out (1) "Look out below," (2) "Look out up forward," (3) "Look out aft."
7. If you drop a stone from the top of a cliff the speed of fall after 3 seconds will be approximately (1) 33, (2) 66, (3) 96, (4) 198 miles per hour, neglecting air resistance.
8. If you fire a gun that weighs 100 times as much as its projectile, and if the bullet has an initial velocity of 800 miles per hour, conservation of momentum tells you that you must be prepared to withstand a kick-back velocity of the gun equal to (1) 1/5, (2) 4, (3) 8, (4) 160 miles per hour.
9. The old gray mare could tell you that one horsepower means: (1) the strength of an average horse, (2) the ability to move 550 pounds, (3) the ability to lift 550 pounds through a height of one foot in one second, (4) the amount of work one horse can do in a minute.
10. A sign painter who weighs 150 pounds is sitting in a sling supported by a single overhead pulley. In order to lift himself higher the painter must pull on the free end of the rope with a force of (1) 75 pounds, (2) 150 pounds, (3) 300 pounds, (4) infinite amount. Neglect the weight of the sling, and friction.
11. If you are a hunter or a soldier, you ought to know that gun barrels are rifled (that is, spiral grooves are cut in them) in order to (1) allow space for expansion of the bullet so it will not stick in the barrel, (2) allow space for the hot gases to escape without bursting the gun, (3) make the gun strong without adding to

its weight, (4) set the bullet into rotation and thus keep it pointed nose-forward during flight.

12. Of the following statements can you pick the one that is true: (1) Centripetal force pulls outward on a rotating body. (2) If a flywheel bursts due to its high speed of rotation, the fragments will fly out radially from the center. (3) An aviator must be strapped into his plane when he loops-the-loop. (4) A spinning gyroscope tends to set itself with its axis parallel to the axis of rotation of the earth.
13. If you traveled to the moon and took your pendulum clock with you, the clock would (1) gain slowly, (2) lose slowly, (3) keep the same time as it did on earth, (4) gain rapidly, (5) lose rapidly.
14. When you see an insect running along the surface of a pond of water without getting his feet wet, you know that this is possible because of (1) capillarity, (2) Pascal's Principle, (3) viscosity, (4) surface tension.
15. If an ice cube is floating on the surface of a glass filled to the brim with water, you may expect that when the ice melts (1) the water will overflow, (2) the water will sink below the brim, (3) there will be no change in the level of the water.
16. Suppose that you have a jar from which air can be exhausted. If there is a cork floating on the surface of some mercury in this jar, your knowledge of buoyancy tells you that when the air is exhausted, thus removing air pressure from the cork, the cork will (1) rise slightly, (2) sink slightly, (3) remain at the same level.
17. The expression, "Where the speed is the greatest the pressure is the least," refers to (1) the pressure of the atmosphere during a hurricane, (2) the flow of liquids and gases, (3) the force with which a speeding automobile presses against the ground, (4) the viscosity of liquids.
18. In comparing an electric current to water flowing in a pipe, we might say that *ampere* is to *volt* as the *flow of water* is to (1) *resistance of the pipe,* (2) *pressure,* (3) *size of the pipe,* (4) *pump.*
19. The unit of electrical resistance is called the (1) volt, (2) ampere, (3) watt, (4) ohm.
20. According to Ohm's Law: (1) amperes = volts × ohms, (2) volts = ohms/amperes, (3) ohms = volts × amperes, (4) volts = ohms × amperes.

21. Of the following, you might expect that the safest place during a thunderstorm would be (1) riding a horse, (2) rowing a boat on the lake, (3) lying in the gutter, (4) riding in a steel railway car.
22. Of the following statements, can you pick the one that is untrue? (1) The Chinese are supposed to have invented the magnetic compass. (2) A compass needle placed on a floating cork will tend to move toward the north pole of the earth. (3) Like magnetic poles repel each other. (4) A piece of iron is attracted to a magnet.
23. An electromagnet will not pick up (1) a safety razor blade, (2) a piece of nickel wire, (3) a brass pin, (4) a carpet tack.
24. Which one of the following statements is untrue? (1) Electric motors and electric meters operate on the same fundamental principle. (2) Ammeters measure electric current. (3) There is a force on an electric charge moving in a magnetic field. (4) Wires carrying electric currents are never attracted to each other.
25. Suppose that electrical energy costs you 5 cents per kilowatt-hour and it takes you half an hour each morning to toast sufficient bread in the 500-watt electric toaster, for the family breakfast. The heat for the toaster then costs you each month about (1) 19, (2) 38, (3) 56, (4) 80 cents.
26. The operation of one modern type of microphone depends on the (1) piezoelectric effect, (2) photoelectric effect, (3) thermoelectric effect, (4) audioelectric effect.
27. If you look at a blue dress under a red light, the dress is likely to appear (1) blue, (2) red, (3) black, (4) white.
28. In one of the following lists the colors of the spectrum are arranged in order of decreasing wave length: (1) blue, violet, green, yellow, red; (2) red, yellow, green, blue, violet; (3) red, green, yellow, blue, violet; (4) red, yellow, blue, green, violet.
29. Ultra-violet light is not effective in (1) penetrating haze, (2) sterilizing air, (3) tanning the skin, (4) producing fluorescence.
30. The phenomenon responsible for the color of a soap bubble is called (1) dispersion, (2) interference, (3) diffraction, (4) refraction.
31. Polarized light is different from ordinary light in that (1) its speed is less, (2) it looks different, (3) it cannot be photographed, (4) its vibrations all lie in one plane.

32. Unless you were directly overhead, you would be likely to miss a fish if you shot at him with a rifle because (1) the bullet would be deflected on entering the water, (2) the bullet would lose its force very rapidly in the water, (3) the fish would appear to be nearer the surface than he actually was, (4) the fish would appear to be farther under the surface than he actually was.
33. If you have a telescope with a magnifying power of 10 diameters, you know that the focal length of the eyepiece is to the focal length of the objective lens as the number, one, is to (1) 10, (2) 1/10, (3) 1, (4) 100.
34. If you look through a pair of field glasses and the image appears colored and blurred, you will know that the glasses are of poor quality because the lenses have not been corrected for (1) astigmatism, (2) spherical aberration, (3) distortion, (4) chromatic aberration.
35. For light to reach us from the moon, a little more than 200,000 miles away, it takes (1) a little more than a second, (2) a little less than a second, (3) about a minute, (4) about 10 seconds.
36. If you were in Paris and someone told you that the temperature was 30° Centigrade, you might be expected to say, (1) "Please start the fire; I'm freezing," (2) "What a lovely spring day," (3) "Hot to-day, isn't it?" (4) "This reminds me of the Mojave desert on a midsummer day."
37. Unless it is of the new forced-circulation type, your hot-air heating system warms the house principally by the process of heat transfer known as (1) convection, (2) conduction, (3) radiation, (4) sublimation.
38. When water pipes burst in the winter, the cause is usually (1) pipes contracting due to the cold, (2) water expanding when its temperature drops below 4° C., (3) water contracting when it freezes, (4) water expanding when it freezes.
39. When you come out of the water and stand around in a wet bathing suit, you are likely to feel chilly even on a warm day because (1) water is evaporating from the wet cloth, (2) water is held in contact with your body, (3) the sunlight cannot penetrate through the wet cloth, (4) the air cannot get to your body.
40. The fundamental cause of most winds is (1) the rotation of the earth, (2) convection currents in the atmosphere due to irregular heating by the sun, (3) the cold air from the earth's poles flowing to lower latitudes, (4) the cooling effect of the oceans.

41. The term *horse latitudes* refers to a region where (1) wild horses are frequently found, (2) the climate is ideal for raising horses, (3) the wind blows irregularly, (4) the storms at sea are especially violent.
42. The dew point is determined by which one of the following properties of the air? (1) humidity, (2) temperature, (3) wind velocity, (4) barometric pressure.
43. An *isobar,* you should remember, is (1) a bar made of ice, (2) a line drawn on a weather map through points of equal temperature, (3) a line drawn on a weather map through points of equal pressure, (4) a region of uniformly high humidity.
44. Sound is transmitted by a kind of wave motion in which particles of air (or other medium) (1) move in circles, (2) travel along with the wave, (3) vibrate in a direction at right angles to the direction in which the wave travels, (4) vibrate in the same direction as that in which the wave travels.
45. If thunder follows one second after a lightning flash, you know that in round numbers the bolt of lightning must have been (1) 100 feet, (2) 1,000 feet, (3) ½ mile, (4) one mile, away.
46. Of the following, can you pick the one statement that is *not true?* (1) The audible range of frequencies is about 20 to 20,000 vibrations per second. (2) The cochlea is a part of the inner ear. (3) The decibel is a unit of loudness. (4) The quality of a musical note depends on pitch and loudness.
47. One of the following frequencies, when sounded simultaneously with the note middle C of frequency 264, will produce distinctly unpleasant dissonance: (1) 132, (2) 266, (3) 340, (4) 396.
48. The iconoscope is a vacuum tube used in television that corresponds to (1) a detector tube in a radio set, (2) a loudspeaker, (3) the human eye, (4) a motion picture screen.
49. Three of the following four statements are true. Can you pick the one that is not true? (1) All of the radium in a sample will have disintegrated in 1,600 years. (2) Radioactivity involves the spontaneous transmutation of one chemical element into other elements. (3) Radium is a dangerous substance to handle. (4) Radium can be used for treatment of disease without bringing the radium supply anywhere near the patient.
50. Vacuum tubes are used for all but one of the following purposes (1) rectification, (2) amplification, (3) production of

images in television receivers, (4) production of x-rays, (5) production of gamma rays.

"True" and "False" Questions

1. A quart of water weighs a little less than one kilogram.
2. The speed of light in empty space is about 186,000 miles per second, and is therefore 300,000 kilometers per second.
3. In round numbers, the distance across the United States from coast to coast is 3000 miles, and is therefore 5000 kilometers.
4. Newton's Third Law of Motion refers to the fact that every object is at all times acted on by at least one pair of equal and opposite forces.
5. Your feet push harder against the floor of an elevator when you are going up at constant speed than when you are going down at constant speed.
6. If you are talking about vector quantities (force, velocity, etc.) 2 plus 2 might equal 3.
7. An iceboat can sail faster than the wind.
8. Aristotle was completely wrong when he said that heavy (dense) bodies fall faster than light ones.
9. Neglecting air resistance, a falling body increases its speed nearly 22 miles per hour for each second of fall.
10. In order to throw a stone a maximum distance along the level you should project it upward at an angle of 45° with the horizontal.
11. Doubling the speed of a body doubles its momentum but quadruples its kinetic energy.
12. Travel to Mars is not theoretically possible.
13. A rocket ship could be propelled more readily in empty space than in the earth's atmosphere.
14. In the scientific sense you are doing work when you carry a sack of flour upstairs, but not when you carry the same sack home from the store along a level street.
15. If you drop a 10-pound stone from a height of five feet above the earth, the stone loses an amount of potential energy equal to 50 foot-pounds, and (neglecting air resistance) has gained a like amount of kinetic energy just before it strikes the earth.
16. The high speed is the reason why "your stomach seems to fall out" when you descend in a fast elevator.
17. If your automobile is stuck in a snow bank, it is wise to spin the rear wheels as rapidly as possible in order to get out.

18. Streamlining of automobiles is not important below speeds of 70 to 80 miles per hour.
19. To overcome air resistance your automobile requires four times as much power at 80 miles per hour as it does at 40 miles per hour.
20. A machine is a mechanical device which does an amount of work greater than the energy put into it.
21. A body moving in a circle at constant speed always has a force pulling inward on it.
22. In a centrifugal cream separator the cream goes to the outside of the rotating pan while the skim milk gathers at the center.
23. The time of swing of a clock pendulum depends on the weight of the bob.
24. Steel is more perfectly elastic than rubber.
25. A thin coating of glue is normally stronger than a thick coating.
26. Without the process of osmosis, a person or animal would soon die.
27. The pressure at the bottom of a tank of oil 10 feet deep would be greater than at the bottom of a tank of water 10 feet deep.
28. A true barometer measures the pressure of the atmosphere and nothing else.
29. It is strictly correct to say that a suction pump sucks water up a pipe.
30. Sunken ships commonly do not go to the bottom of the ocean, but remain floating a short distance beneath the surface.
31. You might expect that a stove or a fireplace would draw better in cold weather than in warm weather.
32. Atoms are made up exclusively of electrons and protons.
33. An electric current always involves motion of electric charges.
34. Metals are good conductors of electricity because they contain a copious supply of free electrons.
35. During a thunderstorm it is wise to take shelter under a tree.
36. Well-designed lightning rods protect a house partly at least because they help to discharge the thunder clouds before a bolt of lightning strikes.
37. Electroplating is a process whereby metal atoms are transferred through a conducting liquid from one metal plate to another, by an electric current.
38. Storage batteries store up electricity.

39. Dry cells contain no moisture.
40. At no place on the earth is the declination of a compass needle equal to zero.
41. The earth's magnetism is almost certainly due to a large iron magnet located near the center of the earth.
42. The electric doorbell depends on an electromagnet for its operation.
43. Many electric motors depend for their operation on the forces between magnets and currents.
44. The kilowatt is a unit of energy.
45. Whenever you stand idly twirling your watch chain, a voltage is generated in the chain due to the earth's magnetic field.
46. Electric motors are constructed exactly like electric generators.
47. Alternating current rather than direct current is supplied to our homes principally because its voltage may be readily stepped up or down by means of transformers.
48. An electrically charged body (for example, your fountain pen after being rubbed on a piece of wool cloth) would be attracted to the pole of a magnet.
49. Electric power is transmitted over long distances at very high voltage in order that the loss of power in the transmission line may be kept small.
50. An induction coil actually contains two separate coils of wire.
51. A modern telephone transmitter depends on an electromagnet for its operation.
52. Light is a form of energy.
53. X-rays are similar in nature to visible light but have a longer wave length.
54. The leaf of a tree is colored green because the leaf generates green light.
55. Light is the result of disturbances within the atoms and molecules of a luminous body.
56. If the sun were blood red, you might expect that the sky would appear red instead of blue.
57. When you are at the beach, a glass umbrella would protect you from sunburn.
58. No two persons ever see exactly the same rainbow.
59. Polarized light looks different to the eye from unpolarized light.
60. The speed of light is less in air than in water.

61. Whenever a ray of light passes from air into glass, the ray is bent.
62. When a ray of light passes obliquely from water into air, the ray is bent.
63. As an object is moved closer to a lens, its real image becomes smaller in size.
64. A person whose eyes are far-sighted can see distant objects with greater clarity than can people with normal vision.
65. If you are near-sighted, you know that the oculist should prescribe for you spectacles with concave lenses.
66. If your spectacles correct astigmatism, you could rotate the lenses in their frames without destroying the effectiveness of the glasses.
67. A magnifying glass is relatively more helpful to a person with normal vision than to a near-sighted person.
68. The human eye accommodates for near and distant objects by changing the distance from lens to retina.
69. The magnifying power of a telescope does not depend on the diameter of its lenses.
70. A microscope which has a magnifying power of 1,000, magnifies the area of an object by a factor of 1,000,000.
71. The stereopticon is a device giving three-dimensional effects from flat pictures.
72. A mirage is caused by the bending of light rays in the heated, rarefied layers of air near the ground.
73. It is possible, but not probable, that heat is a substance rather than a form of energy.
74. A white roof will keep your house cooler in summer than will a black roof.
75. Snow and ice disappear even when the temperature remains continuously below the melting point.
76. A little piece of ice is much more effective than an equal quantity of cold water in cooling a cup of coffee.
77. Under high pressure water freezes at a temperature above 0° Centigrade.
78. It is impossible to raise the temperature of a liquid by making it boil more vigorously.
79. Water always boils at 100° Centigrade.
80. By keeping the refrigerator door open, your electric refrigerator could be used to help cool the kitchen on a hot summer day.

81. The common belief that a "ring around the moon" presages rain can have no foundation in fact.
82. Modern scientific methods enable the weather man to tell you for sure whether your picnic a week from next Sunday will be marred by a thunderstorm.
83. We are uncomfortable on warm, humid days principally because our bodies cannot readily evaporate moisture from the pores.
84. A monsoon is a wind that in summer blows from sea to land and in winter from land to sea.
85. In winter, a falling barometer is likely to indicate cold weather, while a rising barometer is likely to be followed by a thaw.
86. Raindrops are always formed by water condensing around minute particles of impurity in the air.
87. The term *air mass analysis* refers to a comparatively new and superior method of weather forecasting.
88. A great explosion on the sun might eventually be heard here on earth.
89. If an echo from a cliff comes back to you about five seconds after you shout, you know that the cliff is approximately one mile away.
90. The pitch of a musical sound depends only on the frequency.
91. The piano is tuned to the tempered scale, and as a result most of its combinations of notes are slightly dissonant.
92. Reverberation (repeated echoing) in a hall or auditorium is always undesirable from the standpoint of acoustics.
93. The horn of an automobile sounds higher pitched when it is coming toward you than when it is receding from you.
94. If an aeroplane were flying toward you with the velocity of sound, you would not hear anything until the plane had gone past.
95. In a photoelectric cell, electrons are ejected from a metallic surface by means of a beam of light.
96. Space charge cuts down the flow of current in a vacuum tube and is therefore always undesirable.
97. The atmosphere plays an essential role in the transmission of short radio waves over long distances.
98. X-rays consist of electrons reflected from the metal target of an x-ray tube.
99. Overexposure to x-rays or radium is more dangerous than is overexposure to ultra-violet light.

100. Alpha particles are negatively charged and always travel with the speed of light.

"Short Answer" Questions

1. If perpetual motion is impossible, why does the earth continue to rotate and why do the heavenly bodies continue to move?
2. Which of the following are not vector quantities; that is, have no direction associated with them: *weight, mass, force, momentum, velocity, acceleration, energy?*
3. If an aeroplane can make 100 miles per hour in still air, how fast can it go relative to the earth against a headwind of 60 miles per hour?
4. Jack and Jill wish to balance each other on a see-saw. Jack weighs 100 pounds, Jill 50 pounds. If the board is pivoted at the center, and if Jill sits at one end, where must Jack sit?
5. If you were on a train traveling 50 miles per hour and you threw a rock out of the window horizontally (and at right angles to the train) at a speed of 50 miles per hour, how would the rock appear to move, to a person standing alongside the track?
6. Would it ever be possible for a falling body to slow down as it came nearer to the earth?
7. What would happen if all the passengers on a moving boat should suddenly start running toward the bow?
8. If you can stop your car in 20 feet when you are traveling 20 miles per hour, how much distance will you need when you are speeding along at 60 miles per hour?
9. If you can push with a force of 150 pounds, how long a plank would you need to roll a 3,000-pound automobile up onto a platform 2 feet high? (Neglect friction.)
10. If your weight is 180 pounds at the surface of the earth, how much would you weigh if you flew in a rocket ship to the surface of the moon?
11. What is the difference between *cohesion* and *adhesion?*
12. Explain why the water stays in a partially filled glass when a card is placed over the open end and the glass is then inverted.
13. What is the explanation of the expression, "Nature abhors a vacuum"?
14. How does a submarine submerge and come to the surface?
15. What is the name given to electrically charged atoms and molecules in gases and liquids?

16. What is the practical unit of electric current called?
17. If a current of 3 amperes is flowing in a wire of resistance 40 ohms, a voltmeter connected across the ends of the wire would read how many volts?
18. Why are electric light filaments usually made of tungsten?
19. Could you charge a metal rod electrically by holding the rod in your hand and rubbing it with a piece of wool cloth? Why?
20. Does air conduct electricity better on a damp day than on a dry day?
21. How is it possible that 100 volts may sometimes prove fatal, while 10,000 volts may be harmless?
22. Could an electric spark pass through a rubber sheath like that insulating a lamp cord?
23. For what period of time could a current of 2 amperes be drawn from a battery having a capacity of 100 ampere-hours?
24. Would a bit of iron be attracted to a wire carrying an electric current?
25. The nameplate on your vacuum cleaner gives the following information: Voltage, 110; Watts, 330. The current through the cleaner is then how many amperes?
26. The primary coil of a transformer contains 20 times as many turns of wire as the secondary. If 110 volts are supplied to the primary, the secondary will furnish power at approximately what voltage?
27. Can you explain, in 25 words or less, the principle of the dynamo?
28. Why do some stars have a reddish tinge, while others appear white or bluish?
29. How can astronomers tell that the distant stars are made of the same chemical elements that we have here on earth?
30. How does a mixture of blue and yellow light differ in appearance from a mixture of blue and yellow paint?
31. Why does it appear that there are more stars overhead than near the horizon?
32. How could you determine with the aid of a sheet of Polaroid whether a beam of light is polarized?
33. If you wanted to find the focal length of a reading glass, how could you do it very simply?
34. What is the approximate magnifying power of a reading glass of focal length 4 inches?

35. How do opera glasses differ from prism binoculars?
36. If a 1/100 second exposure is required to take a picture with a camera having an *f*-number equal to 4.0, how long an exposure will be required if the *f*-number is increased to 8.0?
37. Do we see the sun before it rises above the horizon in the morning? Can you explain your answer?
38. Why are cracks frequently left in sidewalks, bridges, pavements, and the like?
39. Explain why two pieces of ice melt quickly when they are rubbed together vigorously.
40. How many calories of heat are required to heat 100 grams of water from 20° C. to 100° C.?
41. Describe what happens in one of the cylinders of your automobile engine during two complete revolutions of the engine?
42. At a temperature of 20° C. (68° F.) saturated air contains about 17 grams of water in each cubic meter. How many grams of water vapor are there in a small room, $3 \times 4 \times 5$ meters, at 20° C., if the relative humidity is 50 per cent?
43. Why does simply covering a plant tend to protect it from frost?
44. If there were little or no atmosphere, and if the surface of the earth were dry, would the earth be warmer or cooler than it is now?
45. If the note *F* has a frequency of 352 vibrations per second, what is its wave length in air at a temperature of 20° C.? (The velocity of sound at that temperature is 1130 feet per second.)
46. Two piano strings have the same mass and the same length, but string No. 1 is under greater tension than is string No. 2. Which string will emit the note of higher pitch?
47. Why does a jug change its tune while it is being filled with water?
48. A short-wave radio broadcasting station operates on a wave length of 15 meters. What is its frequency in kilocycles?
49. Explain how the circuit inside your radio is altered when you tune the radio to receive waves of a certain frequency.
50. What happens when a radium atom disintegrates and thereby exhibits radioactivity?

Answers to "Choice" Questions

The numbers in parenthesis refer to the number of the correct statement in the original question. Page numbers refer to the page where the discussion is related to the question.

1. (1). Page 6.
2. (3). Page 7.
3. (3). 50 kilometers per hour is about 30 miles per hour. Page 7.
4. (2). Page 10.
5. (1). Page 11.
6. (1). Relative to the ship, the wrench would drop straight down. Page 15.
7. (2). Page 23.
8. (3). Page 27.
9. (3). Page 31.
10. (1). Each of the two ropes (one supporting the painter and one on which he pulled) would carry a load of 75 pounds. Page 45.
11. (4). Page 50.
12. (4). Page 50.
13. (5). The acceleration of gravity is only 1/6 as great on the moon as on earth. Page 53.
14. (4). Page 61.
15. (3). Page 74.
16. (2). The buoyant effect of the air is removed. Page 75.
17. (2). Page 77.
18. (2). Page 86.
19. (4). Page 86.
20. (4). Page 86.
21. (4). Page 94.
22. (2). The forces of attraction are equal and opposite on the two ends of the needle. Hence the needle will *turn* so as to align itself with the magnetic meridian; but it will not tend to *move* northward.
23. (3). Brass is non-magnetic. Page 109.
24. (4). Page 106.
25. (2). Page 119.
26. (1). Page 123.
27. (3). Page 137.
28. (2). Page 135.

29. (1). Page 144.
30. (2). Page 148.
31. (4). Page 150.
32. (3). Page 156.
33. (1). Page 170.
34. (4). Page 171.
35. (1). Page 133.
36. (3). 30° C. is 86° F. Page 184.
37. (1). Page 190.
38. (4). Page 194.
39. (1). Page 198.
40. (2). Page 214.
41. (3). Page 216.
42. (1). Page 221.
43. (3). Page 229.
44. (4). Page 236.
45. (2). Page 237.
46. (4). Page 240.
47. (3). Page 246.
48. (3). Page 277.
49. (1). Only half of the radium will disintegrate in 1,600 years. Page 284.
50. (5). Page 286.

Answers to "True and False" Questions

1. True. Page 7.
2. True. Page 7.
3. True. Page 7.
4. False. Page 10.
5. False. True only for *accelerated* motion. Page 13.
6. True. Page 14.
7. True. Page 19.
8. False. Page 23.
9. True. Page 23.
10. True. Page 26.
11. True. Page 32.
12. False. Page 29.
13. True. Page 29.
14. True. Page 31.
15. True. Page 32.

16. False. It is the acceleration; there is no unusual sensation at constant speed. Page 35.
17. False. Page 39.
18. False. Page 40.
19. False. Eight times. Page 39.
20. False. Page 42.
21. True. Page 47.
22. False. Page 47.
23. False. Page 52.
24. True. Page 59.
25. True. Page 60.
26. True. Page 64.
27. False. Oil is less dense than water. Page 66.
28. True. Page 69.
29. False. Page 71.
30. False. Page 75.
31. True. In cold weather, the warm air rising in the chimney is relatively less dense with respect to the outside air. Page 76.
32. False. Page 82.
33. True. Page 83.
34. True. Page 87.
35. False. Page 94.
36. True. Page 95.
37. True. Page 101.
38. False. They store chemical energy. Page 102.
39. False. Page 103.
40. False. Page 111.
41. False. Page 110.
42. True. Page 113.
43. True. Page 115.
44. False. Page 119.
45. True; but the voltage is very small. Page 121.
46. False. Page 122.
47. True. Page 125.
48. False. There is no force between magnets and stationary electric charges.
49. True. Page 126.
50. True. Page 128.
51. False. Page 130.
52. True. Page 133.

53. False. They have shorter wave length. Page 136.
54. False. Page 135.
55. True. Page 139.
56. True. Only red light would be available for scattering. Page 143.
57. True. Page 145.
58. True. They see light reflected from different raindrops.
59. False. Page 151.
60. False. Page 155.
61. False. The ray is not bent if it strikes the surface at right angles.
62. True. Page 155.
63. False. Page 160.
64. False. Page 165.
65. True. Page 166.
66. False. Page 167.
67. True. Page 166.
68. False. Page 164.
69. True. Page 170.
70. True. Page 167.
71. False. The stereopticon is a magic lantern.
72. True. Page 177.
73. False. Page 185.
74. True. Page 191.
75. True. Page 193.
76. True. Page 194.
77. False. Pressure lowers the freezing point. Page 195.
78. True. Page 197.
79. False. Page 198.
80. False. Page 205.
81. False. Halos are caused by ice or mist particles that are likely to precede a storm.
82. False. Page 207.
83. True. Page 209.
84. True. Page 218.
85. False. Pages 219, 220.
86. True. Page 223.
87. True. Page 229.
88. False. Page 235.
89. False. 1/2 mile. Page 237.

90. False. Page 239.
91. True. Page 248.
92. False. Page 259.
93. True. Page 260.
94. True. Sound and plane would arrive together. Page 261.
95. True. Page 263.
96. False. Page 268.
97. True. Page 272.
98. False. Page 279.
99. True. Pages 282, 287.
100. False. Page 286.

Answers to "Short Answer" Questions

1. There is no retarding force (page 9); perpetual motion has to do with the Conservation of Energy (page 33), and the heavenly bodies expend little energy.
2. *Mass* and *energy*. Page 14.
3. 40 miles per hour. Page 16.
4. Half way between the pivot and the end. Page 21.
5. It would start out horizontally at a speed of 70.7 miles per hour, moving forward at an angle of 45° with the train. It would, of course, begin to drop immediately. Page 25.
6. Yes, due to increasing air resistance as the atmosphere becomes more dense. Meteors and, sometimes, projectiles do slow down.
7. The boat would slow down. Page 27.
8. 180 feet. Page 32.
9. 40 feet. Page 44.
10. 30 pounds. Page 54.
11. Cohesion is the attractive force between like molecules; adhesion between unlike molecules. Page 60.
12. A little water runs out, leaving a partial vacuum inside. Air pressure on the bottom of the card then supports the water.
13. Atmospheric pressure here on earth gives us that impression. Page 67.
14. It submerges by filling its ballast tanks with water; it rises by forcing the water out of the tanks with compressed air. Page 75.
15. Ions. Page 83.
16. The ampere. Page 84.

17. 120. Page 86.
18. Tungsten melts, and evaporates only at a high temperature. Page 87.
19. No. The charge would immediately flow off to ground through your body. Page 88.
20. No. Because of moisture condensed on the surface of insulators, electric charges leak off more rapidly on damp days; but the air contains no more free charges (ions and electrons) than usual.
21. Electricity is dangerous only when a current of 1/10 ampere or more is available. Page 97.
22. Yes, if the voltage were high enough or the rubber were old and cracked.
23. About 50 hours. Page 105.
24. Yes, but feebly. The magnetic field becomes stronger close to the wire. Iron is always attracted into a region of stronger field.
25. 3. Page 119.
26. 5 1/2. Page 126.
27. Voltage is generated in any wire cutting across magnetic lines of force. Page 121.
28. Cooler stars are reddish; the hotter ones bluish. Page 139.
29. By the characteristic spectral colors emitted by the incandescent vapors. Page 142.
30. Blue and yellow light appear white. Blue and yellow paint appear green. Page 138.
31. Light from the fainter stars near the horizon is scattered out and lost in the greater thickness of atmosphere through which the light must travel to reach us.
32. Pass the beam through Polaroid, and rotate the sheet of Polaroid. The beam will be extinguished each half revolution if the light is polarized. Page 151.
33. Project the image of a distant object on the wall. Focal length is the distance from lens to image. Page 160.
34. 10/4 or 2 1/2. Page 168.
35. The eyepiece lens is concave instead of convex. Page 170.
36. 4/100 or 1/25 second. Page 173.
37. No. We do not see the sun until nearly eight minutes after it rises; though the bending of the rays in the earth's atmosphere reduces this time somewhat. Page 176.

38. To allow for expansion and contraction during warm and cold weather. Page 182.
39. Friction supplies the necessary heat of fusion. Pages 185, 194.
40. 8,000 calories Page 186.
41. (1) Gasoline and air are sucked in on the downstroke of the piston; (2) the explosive mixture is compressed on the upstroke; (3) the explosion drives the piston down; (4) the burned gases are expelled. Page 203.
42. 510 grams (more than a pound). Page 209.
43. The covering traps heat radiation and maintains a slightly higher temperature. Page 222.
44. As on the desert and at high altitudes, it would be very cold at night and very hot in the daytime. Page 228.
45. 3.2 feet. Page 234.
46. String No. 1. Page 248.
47. Length and shape of the air column changes. Pitch becomes higher as the column is shortened. Page 251.
48. 20,000. Page 272.
49. Inductance and capacitance of the receiving set is altered until the natural frequency of oscillation is the same as the frequency of the incoming waves. Page 273.
50. The nucleus of the atom splits up into two parts; an alpha particle and the nucleus of a radon atom. Page 285.

INDEX